# Assessment of Condition-Based Maintenance in the Department of Defense

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# Executive Summary

Condition-based maintenance (CBM) is a form of proactive equipment (e.g., weapon systems) maintenance that forecasts incipient failures. CBM is a set of maintenance actions based on real-time or near real-time assessment of equipment condition obtained from embedded sensors and/or external tests and measurements using portable equipment. It contrasts with reactive (run-to-fail) and preventive (scheduled) maintenance concepts. The Navy identifies the purpose of a CBM strategy as performing maintenance only when there is objective evidence of need, while ensuring safety, equipment reliability, and reduction of total ownership cost; we agree with this.

As a maintenance strategy, CBM is of interest because it can help optimize Department of Defense (DoD) maintenance programs. Using CBM can decrease false alarms and prevent unnecessary maintenance. CBM has the potential to improve operational readiness and mission reliability.

We developed a set of characteristics that identify a range of CBM capabilities. These characteristics include hardware (e.g., sensors and computers), software (including decision support capability), and communications (e.g., data buses and communications links). A subset of these characteristics is used to define basic CBM capabilities; the entire set defines fully robust CBM capabilities. We then assess four strategic DoD CBM programs within the context of these characteristics:

- Army — Army Diagnostic Improvement Program (ADIP)
- Navy — Integrated Condition Assessment System (ICAS)
- Joint — Joint Strike Fighter Prognostic Health Management (JSF PHM)
- Joint — Integrated Mechanical Diagnostics - Health Usage Monitoring System (IMD-HUMS).

The JSF PHM capabilities promise to be the most robust and reflective of the full potential of CBM for DoD weapon systems. It should be noted that while this is a developmental program, still in competition, it appears that CBM will be a successful, fundamental concept within the aircraft's maintenance and logistics programs. The other programs, too, contained worthy elements which we identify and discuss.

DoD's legacy systems pose substantive challenges to CBM implementation. Onboard (e.g., embedded) sensors often require substantial and costly modifications; absence of installed communication buses can frustrate data collection and analysis. Off-board (e.g., manual data gathering and analysis) approaches may not be as comprehensive but can support basic CBM strategy. DoD appears interested in pursuing both these approaches for its legacy systems.

The Military Services are, in fact, testing CBM technologies with a number of prototype and developmental programs. Several of these programs, in addition to the four assessed, are at various stages of actual development and evaluation.

Our overall assessment of the CBM concept and DoD's moves toward implementation lead us to conclude that the overall movement can benefit from:

- Increased awareness of CBM concepts and Service approaches
- Improved coordination of Service initiatives, and
- Additional advocacy in the form of policy guidance.

To achieve these benefits, we recommend that the ADUSD(L) MPP&R encourage, incentivize, and help focus inter-Service collaboration on CBM strategies. As a first step, we suggest that the Maintenance Technology Senior Steering Group (MTSSG) be made aware of and become involved with CBM exploration. We also recommend: (1) continuing use of the National Defense Industrial Association (NDIA) Systems Engineering Committee structure, (2) improving awareness of CBM using the ADUSD(L)MPP&R web site, (3) developing a CBM track at the year 2000 DoD Maintenance Symposium, and (4) considering additional maintenance policy development regarding CBM.

# Contents

# Introduction

This briefing results from our evaluation of the transition of military maintenance below depot level. It addresses one of the many subjects involved in a move away from a doctrine largely established in the 1960's for preventive maintenance, to the technology-enabled processes available to us today, almost a half-century later. Our focus is on the organizational (O) level of maintenance and, in particular, how weapon systems and equipment can be built with on-board computing power that facilitates real-time awareness of equipment condition. This "embedded" intelligence mirrors the advances in smart weaponry to achieve new levels of maintenance capability. Current military maintenance practices are generally effective, but often with ad hoc work-arounds and high cost in labor and inventory; Condition-based maintenance (CBM) strategies can get desired results more effectively and efficiently.

During our research, we surveyed a wide range of technical development efforts and studies on the subjects of integrated diagnostics, prognostics, and CBM. Development projects ranged from Advanced Concept Technology Demonstration projects, such as the Joint Advanced Health Usage & Monitoring System (JAHUMS), through the many research and development (R&D) programs sponsored by military service agencies and organizations, such as the Deputy Under Secretary of Defense for Science and Technology, the Office of Naval Research, and the Defense Advanced Research Projects Agency. We reviewed the DoD-sponsored report on Open Systems Architecture for Integrated Diagnostics Demonstration (OSA-IDD) and its associated case studies. We then narrowed our research efforts to focus on what we now characterize as the major service-level development programs for CBM.

In this report, we look at the technology underpinning new maintenance capabilities and several key Service programs that are using these technologies to lead the way to substantially higher levels of support capability. These key programs have broad scopes with regard to the amount of technology and integration, long time horizons, and substantial budget resources.

We conclude by identifying significant technology issues that may systemically affect all Service maintenance programs. And we note the "best practices" in these programs that we believe could be guideposts for all programs in developing contemporary maintenance processes.

### Motivation for Maintenance Process Re-examination

- Joint Vision 2010 & Focused Logistics
  - JV2010 is driving logistics reinvention and maintenance process improvements .
  - Focused Logistics Section
    - ↓ Anticipatory Maintenance
    - ↓ Agile
    - ↓ Velocity-Based
    - ↓ Lower Costs
- Service Response
  - The Services are re-engineering maintenance processes through technology insertion and doctrinal change for condition-based maintenance programs.

## Motivation for Maintenance Process Re-examination

Joint Vision (JV) 2010 articulated the strategic intent of the Joint Chiefs of Staff to guide United States (U.S.) military forces development over the next ten years . It describes a network-centric battlefield that leverages information technology to achieve affordable combat power. Focused Logistics, a section of JV2010, envisions an end-state that requires fewer, more effective maintainers and more rapid logistics response than we now have—at less than today's costs. (Note: JV2020, recently published, is consistent with this view of logistics.)

Military service maintenance practices have roots dating to World War II when equipment was far less complex. Over the ensuing decades we have seen enormous technical change in equipment, but correspondingly far less change in maintenance management style and practice. In order to achieve the vision of Focused Logistics—anticipation, agility, velocity, etc.—the underpinning maintenance management processes must be updated. Instituting CBM at the Service level is a key part of that process.

The Services recognize the shortcomings of existing processes and are attempting to bring new technology and the practices of CBM to bear on the challenge. The Service CBM programs we reviewed address new weapon systems and retrofitting new CBM technologies into legacy systems where practicable.

CBM promises to detect changes in equipment condition or operating parameters that will allow prediction of impending failure or remaining operating life. With this information, corrective maintenance can be scheduled rather than awaiting failure of the item or system.

In brief, there are enormous implications in this capability. Operating units could centralize more of their repair operations; reparables will be removed before suffering expensive catastrophic failure; trouble-shooting to identify failing components will be dramatically more effective. Mission completion rates will also improve. All of these benefits lead to significant reductions in support costs and explain the Service interest in the technologies.

CBM Technology can help achieve the JV2010 end-state for maintenance capability. Industry has been employing condition-monitoring and CBM for many years, and has shown they work. Similarly, Naval aviation has been very active in addressing condition-monitoring on selected airframes and with specific monitoring techniques. At this point, DoD needs to bring together the technology and the doctrine and policy to employ it well.

> **Current Maintenance Problems and CBM Solutions**
>
> - Existing preventive maintenance programs in the Military, derived decades ago, have these characteristics:
>   - High Cost, Labor Intensive
>   - Perform unnecessary maintenance
>   - Do not prevent catastrophic failure
>   - Have high rates of CND / RTOK / NEO.
>
> - CBM technology and processes offer the capability to mitigate many of these problems, and in addition:
>   - Decrease false alarms
>   - Increase operational availability and mission reliability
>   - Reduce logistics footprint
>   - Maximize return on capital invested, as measured by quantitative and non-quantitative benefits:
>     - ↓ Cost Savings
>     - ↓ Operational Availability / Mission Reliability.

# Current Maintenance Problems and CBM Solutions

Current military maintenance doctrine and practices originated decades ago. Most Service maintenance manuals identify the process as the doctrine of preventive maintenance. It can be described as a time-based process of fixed-interval inspection and repair schedules that can result in undesirable consequences as indicated. These consequences impact two broad areas: cost and operational availability.

## Cost Avoidance

A number of characteristics of today's military maintenance environment at the organizational level are principal cost-drivers. These characteristics include being labor and inventory intensive, performing unnecessary removals (i.e., removing components prematurely)–with the unproductive labor that entails, not preventing catastrophic failures, and contributing to high rates of can not duplicate (CND) malfunctions (when components are sent to higher levels of maintenance). These characteristics drive unnecessary labor, transportation and inventory costs.

High rates of CND malfunctions (also known as NEOF, No Evidence of Failure–and RTOK, Retest Okay) are not driven by inadequate maintenance practices alone; system design contributes to the problem as well. CBM can offset, but not completely compensate for, underlying poor system design. That is one reason we have the Engineering Change Proposal (ECP) process, but CBM technology mitigates many of these problems and offers other capabilities as well.

## Increased Mission Reliability

These faults in the maintenance environment detract from sustaining high readiness rates, the bottom line in combat effectiveness. Well-designed CBM and prognostics (as opposed to the injection of technology for its own sake), combined with autonomic logistics (a term we will define later), can reduce false alarm rates, shrink inventory requirements, and improve the turn-around rate for mission equipment. Such results can improve sortie generation rate (SGR) and other measures of combat power.

## CBM Technology Promise

CBM technology impacts more than just direct costs. It can mitigate other negative consequences of system design and maintenance practices that may not be so easily quantified. Having well-designed equipment and well-designed CBM for that equipment reduces high false alarm rates (and avoids potential collateral damage when performing removals). This in turn reduces the logistics footprint (less inventory, less test equipment, fewer maintainers). Similarly, readiness improves as weapon systems are not put into maintenance unnecessarily. In the Joint Strike Fighter-Predictive Health Management (JSF-PHM) program, system design and CBM design go hand-in-hand to address all these issues and more. In industry, CBM employment is a consequence of focusing on getting maximum performance from invested capital in performing assets. CBM employment in military applications that has been thought out up front will not only be more cost-effective, it will meet mission requirements for operational availability of equipment with a reduced logistics footprint. This maximizes both quantitative and qualitative benefits of CBM.

## Definition and Purpose

- Definition
  - CBM is a set of maintenance actions based on real-time or near real-time assessment of equipment condition, which is obtained from embedded sensors and/or external tests and measurements taken by portable equipment.

- Purpose:
  - OPNAV INST 4790.16, Condition-Based Maintenance (CBM) Policy, 6 May 1998:
    - "The purpose of CBM strategy is to perform maintenance only when there is objective evidence of need, while ensuring safety, equipment reliability and reduction of total ownership cost."

# Definition and Purpose

CBM is initiated by sensing equipment condition. Our definition of CBM describes it as a set of actions taken as a consequence of knowing the current operating status of the equipment. Determining current equipment operating status is accomplished in three basic ways:

- By using sensors and computers that are embedded into the operating equipment and monitored on-the-fly,
- By applying portable sensing equipment that marries up to an interface or wiring harness to "read" embedded sensors, or to apply the sensor itself, such as a stand-alone wear measurement,
- By using manual gauges or instruments, such as a tire-wear gauge

The most succinct purpose statement we have seen is that published by the Department of the Navy as cited in OPNAV Instruction 4790.16 for CBM policy and shown above.

We should be clear as to the intent of CBM, as well as its capability. The intent of CBM, as mentioned in the Navy purpose statement, is to perform maintenance only when there is objective evidence of need. The technical capability of CBM is to identify current equipment conditions. What we do with these condition indicators is more than a matter of being able to schedule maintenance or forecast failure. Done right, with objective evidence of need in hand, we forecast or schedule maintenance tasks. However, steps must be taken beforehand—before CBM is applied to a given task—to ensure it is a cost-effective task in the first place. We explore this further later.

**CBM is Predictive Maintenance**

- Traditional military maintenance is focused on preventive maintenance; CBM is based on predictive maintenance.

| | Maintenance Processes | | | |
|---|---|---|---|---|
| | Reactive | Proactive | | |
| Category | Run-to-Fail | Preventive | Predictive | |
| Subcategory | Fix when it breaks | Scheduled maint. | CBM | Prognostic |
| When Scheduled | No scheduled maintenance | Static: maintenance based on a fixed time schedule for inspect, repair, and overhaul | Dynamic: maintenance based on current condition | Dynamic: maintenance based on forecast of remaining equip life |
| Why Scheduled | | Failure modes and equipment maintenance requirements predicted during design | Maintenance is needed now based on real-time evidence to prevent equipment degradation | Maintenance need is probable within next mission time |
| How Scheduled | | Modeling and simulation; no real-time feedback loop | Continuous collection of condition data | Forecast of remaining equipment life based on actual stress conditions |

## CBM Is Predictive Maintenance

From the 1960's to the present, major efforts in maintenance reengineering have taken their shape in commercial industry. The roots of CBM are attributed to the pioneering work in commercial aviation that led to development of CBM theory and practice as we know it today. To further define CBM, and place it in perspective, we use the framework of reactive and proactive maintenance that leading authors and practitioners in the field of modern industrial maintenance practice generally agree upon. We expanded the taxonomy to describe the key differences in the categories.

CBM and prognostics are two forms of proactive maintenance; both can forecast incipient failures. The key distinction between CBM and prognostics is that CBM identifies a failure that will occur shortly, based on current condition indicators, while prognostics forecasts remaining equipment life, based on stress loading (i.e. flight hours at specific "G" loads or time-stress measurements based on a cumulative vibration curve, as opposed to flight hours only). Another way of viewing the distinction between CBM and prognostics is that CBM determines a forecast of impending failure from physically measured indicators on the equipment, while prognostics adds the capability to forecast remaining equipment life.

The ability to forecast remaining equipment life appears simple enough, particularly if a log of usage in hours or miles is kept which can be compared to a ceiling number of hours or miles, or if a graph of operating characteristics can be compared to threshold values. But this is misleadingly simple and there are certain fallacies in such an approach.

One fallacy of estimating remaining equipment life from a journal of usage is that it assumes the component fails according to a wear-out schedule, e.g., at x hours/miles. This may not be the case. A ceiling usage based on hours/miles does not factor in stress loads that can prevent realization of those hours/miles. The notion of stress loading that significantly diminishes mean time between failure (MTBF) is not new. Professional logistics engineers are familiar with the distinction between calculated MTBF and operational MTBF, in which operational MTBF may be lower by a factor of 20 or more than the calculated MTBF.

Prognostics attempts to know and factor the stress environment into remaining life calculations as a means of augmenting condition-monitoring information. A prognostic system may anticipate a failure further down the road than that which is predicted by current equipment conditions.

The proceedings of the IEEE Aerospace Conference in March of 2000 contain a number of papers reporting on prognostic research and development.[1]

[1] IEEE Aerospace Conference Proceedings, Big Sky, Montana, March 2000, http://www.aeroconf.org/.

Advanced CBM Technologies

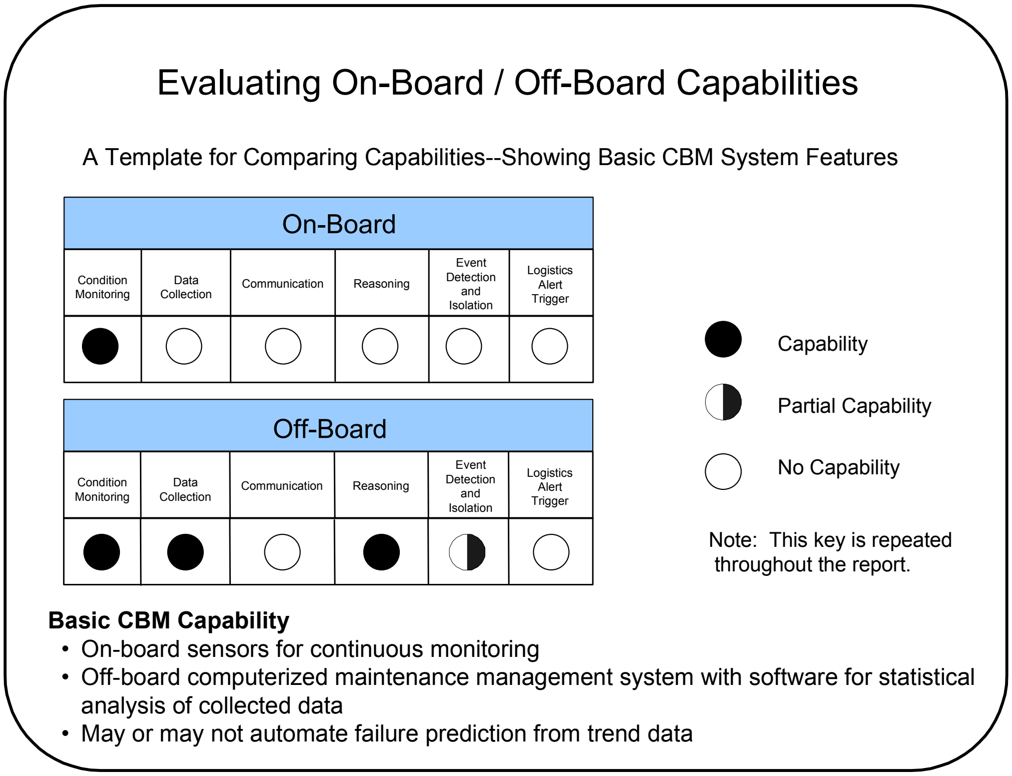
Sensor Technology

| Sensor Technology | Application |
|---|---|
| **Ultrasound** | Wall Thickness Corrosion, Hydraulic/Pneumatic Leaks, |
| **Infra-Red** | Motors, Pumps, Bearings, Electronics: Heat Stress |
| **Ferrography** | Oil Analysis, Detection of Wear-Metals |
| **Laser** | Structures: Joint Alignment/Separation, Particle Detection |
| **Eddy Current** | Anomaly Detection: Turbine Blade Cracking |
| **Gas Chromatography** | Exhaust Analysis |
| **Acoustic** | Plastic Deformation of Metals, Seal Leaks |
| **Spectrum Analysis** | Electronic Emissions |

# Advanced CBM Technologies

Advanced technologies, such as those cited in this chart, are not necessarily new. But the availability of such technologies in highly reliable, miniaturized or micro-miniaturized form is new. The implication of such miniaturization for CBM is that more and more kinds of technology may be embedded in on-board operating weapon systems and used for condition-monitoring in real time.

Some technologies are more useful or more prevalent than others. For example, although not cited as an “advanced” technology, vibration monitoring is an important technology for condition-monitoring of equipment that contains rotating mechanisms or propulsion systems. In various forms, vibration is key to monitoring the health of helicopters, jet aircraft, ground vehicles, space vehicles, surface ships and submarines. If it rotates, it vibrates, and the harmonics of vibration yield insight into predicting failure.




# Evaluating On-Board / Off-Board Capabilities

To get a sense of how weapon systems compare in employing CBM capability, we first look at on-board and off-board computing capabilities. By "on-board," we mean embedded into the operating equipment to be monitored. This way of characterizing CBM capability enables an analysis of how information is collected, analyzed, and acted upon in real time. The more embedded the technology, the more real-time it can be.

Basic CBM capability facilitates equipment failure prediction via off-board trend analysis and links, through a man-in-the-loop system, to inventory decisions. Condition data is collected either from sensors embedded on-board, or from sensors that are applied with portable sensing equipment. Logistics support decisions are not automated. Basic CBM capability doesn't involve interpreting the data on-board, nor linking that data in real time to a remote site, nor integrating the trend analysis directly to the logistics support system.

## How CBM Works

The spectrum of CBM capability ranges from very limited capability to sophisticated capability. Basic CBM capability provides for monitoring selected systems or subsystems, collecting a history of monitored parameters and analyzing the data for trends. When a trend should be a matter of concern is determined by setting values for high-low thresholds, which is a key issue for predictive capability. Often this may be a judgment call on the part of the system owner.

In this report, we describe three ways to view CBM capabilities that help differentiate the CBM systems we assessed:

- On-board/off-board capabilities
- Diagnostic and predictive functionality
- Hardware/software block diagrams.

Each of these three viewpoints looks at different perspectives of the same thing, the CBM capabilities we are describing. On-board/off-board features describe how and where condition-monitoring data is collected and processed. The table on diagnostic and predictive functionality describes the kind of fault processing the CBM system accomplishes. The hardware/software block diagrams give an overview of the highlights of the system architecture, which also helps illustrate what the key components of the system are and where open systems architecture (OSA) concepts come into play.

Diagnostic / Predictive Functionality

Diagnostic Function Table

| Functionality | Basic CBM Capability |
|---|---|
| Fault Detection | ● |
| Fault Isolation | ◑ |
| Fault Prediction | ● |
| Fault Reporting | ● |
| Usage Monitoring | ● |
| Fault Assessment | ○ |
| Fault Recovery | ○ |
| Sensor-Coupled IETM | ○ |
| Logistics Trigger | ○ |

## Diagnostic / Predictive Functionality

### Basic CBM Capabilities

There is a range of diagnostic capability in CBM systems that progresses into more powerful prediction and actions as predictive sophistication increases. As shown in the chart, basic CBM capability includes fault detection and some degree of fault prediction, along with reporting and usage.

### Fault Detection

When on-board, fault detection can be accomplished in two ways, directly from sensors, or through a software/hardware system that infers a fault condition, or forecasts it. Software to accomplish the inferencing process is typically either model-based or neural-net based. The JSF Prognostic Health Management system design concept uses model-based reasoning software. JAHUMS is an Advanced Concept Technology Demonstration for helicopter health management that uses a neural-net software approach.

### Fault Isolation

While fault detection can be accomplished on-board, it takes sophisticated equipment to isolate failures on-board. Only the JSF-PHM system, of all those we looked at, does so with a high degree of confidence, based upon multiple sensor inputs or a hard sensor combined with reasoning derived from the state of other components. The principal alternative method of fault isolation is what O-level maintenance is all about: troubleshooting the symptom, identifying the cause, and then repairing it.

Fault isolation is traditionally accomplished off-board by a maintainer equipped with tools, portable equipment, and a technical manual to guide the troubleshooting process. Modern off-board troubleshooting can now be technologically enabled through the use of an interactive electronic technical manual (IETM) capability that interrogates embedded sensors or software reasoners and uses that data automatically in the troubleshooting process. Only a few IETMs with this capability currently exist.

### Fault Assessment and Fault Recovery

Fault assessment refers to on-board assessment of the fault with respect to current mission capability. Fault recovery means that the weapon system or equipment being monitored has software and hardware that can either invoke redundant functionality or make decisions about operating with some degraded mission capacity. Only the JSF PHM program directly addresses this capability, as PHM evolves in concert with the systems engineering of the aircraft itself. The IMD-HUMS helicopter program is the other CBM program surveyed that does fault reporting, focusing principally on flight safety issues.

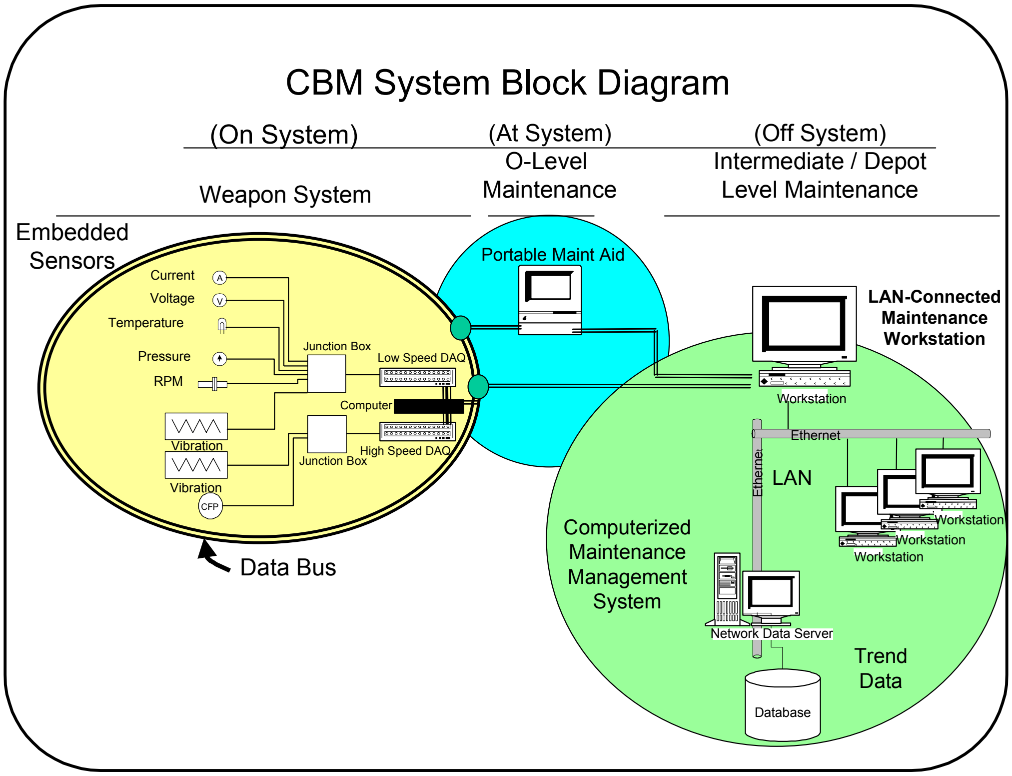
### IETMs

IETMs come in many forms, despite numerous attempts on the government's part to standardize them. The CBM programs reviewed for this report all use IETMs; the nature of the IETMs differ, as they should. They are standardized to the degree that they all use a form of the Hyper-text Markup Language (HTML) and its subset, SGML (Standard Generalized Markup Language). They differ as to how they perform troubleshooting and repair, which is what we are concerned with from a CBM perspective.

All IETMs here are designed to take the old paper technical manual (TM) concept and put it into computer presentable and manipulable form on a Portable Maintenance Aid (PMA). Each program has its own approach on how to do that. The fundamental differences among IETMs are (1) how they interface to the weapon system to be worked on, and (2) whether or not they can use the embedded CBM hardware and software to assist the process. Three of the four CBM systems we report on here use embedded CBM hardware and software. JSF PHM and IMD-HUMS use data collected from the embedded system to aid the troubleshooting process. ADIP connects directly to the embedded sensor system. ICAS makes the troubleshooting and repair instructions available on-line from a server, but does not tie the CBM process to the maintenance instructions.

### Logistics Information System Integration and Automated "Triggering" Decisions

Last in our CBM diagnostic functionality table—and at the most sophisticated level of CBM capability—is the ability to trigger the inventory process automatically, based on decision support software. The logistics "trigger" can be man-in-the-loop decision-making, but at the most sophisticated level of development, the CBM system is integrated with the service-level logistics information system and triggered automatically. A few of the leading CBM systems are implementing logistics system integration. Two approaches, the JSF PHM system and the Predictive Maintenance Module in the Army ADIP, are developing logistics information system integration with automatic decision triggers.




# CBM System Block Diagram

## OVERVIEW

For the CBM system block diagram, we introduce the terms of on-system, at-system and off-system (system in this latter instance referring to weapon system), instead of using the on-board/off-board terms. This stems from the need to introduce the use of portable equipment that performs condition monitoring and runs the IETM.

- On-system – the embedded (on-board) sensors and computers from which condition-monitoring data is collected. This also includes the data bus or wiring harness and connectors that carry the signals from the sensors.
- At-system – the portable maintenance aid and/or portable sensoring equipment used periodically to check equipment health.
- Off-system – this is synonymous with off-board, except concerning Navy ships. Navy ships keep the workstations on-ship; so; from a NAVSEA perspective, everything is on-board. We will call this shipboard when discussing Navy surface ship CBM.

## Open Systems Architecture

A block diagram can help visualize the key interfaces and standards that are fundamental to open systems architecture design. The standards committees of the Institute of Electronic and Electrical Engineers (IEEE) and the Society of Automotive Engineers (SAE) play key roles for defining interface and component standards (as do others). We highlight key areas where these standards underpin an open architecture design.

## Data Bus

The data bus specification is a key design element to achieving open systems architecture.

- Physically, a data bus replaces part of a weapon system wiring harness and significantly reduces harness wiring. It may be fiber-optic or wire.
- Functionally, the data bus is a local area network (LAN) for the vehicle and can have redundant capability for fault-recovery purposes, as it does in most modern fighter aircraft and ground fighting vehicles.
- From an interface standpoint, a data bus is an interface portal providing access from external devices to embedded sensors and computers.

There are only a handful of data bus definitions. If the weapon system employs an industry standard data bus, such as the J1708 or J1939 data buses specified by SAE, or the Mil-Std-1553 data bus, then the hardware interface to the embedded computer is a well-described entity which facilitates third-party commercial off-the-shelf (COTS) component suppliers. The data bus does not have to comply with an industry standard to enable open systems, as long as the definition of signals is openly available, such as the NAVSEA Integrated Carrier Advanced Network (ICAN) program, which is now specified for a fiber-optic backbone in the new generation of aircraft carriers.

## Messages on the Bus

Open Architecture design is facilitated by specifying the message traffic on the data bus in some standard fashion. SAE has learned from the earlier Mil-Std-1553 data bus experience in this regard. SAE has defined companion message protocols for the hardware bus. Mil-Std-1553 does not do this, which forces a retrofit systems integrator or CBM developer to learn the message protocol for every subsystem, each of which typically differs significantly from the other.

## Embedded Sensors

Fundamental to all CBM systems is a suite of embedded sensors of various types. The more sophisticated the system, the more diverse the sensor technologies and the greater the density of sensors employed. The IEEE now specifies a sensor object model that defines sensor features. The SAE does this also.

Older weapon systems accessed sensors directly via a wiring harness routed to a common connector; newer systems use a data bus. Some ground systems in the Army have both, which may complicate access to data. Some older aviation systems are also only partially integrated, again limiting data access.

### Embedded Computers

All new weapon systems employ on-board computers, in many cases, in conjunction with data acquisition channels and data storage capacity. Embedded computer design generally follows industry standards, depending on the form factor, processing power, storage requirements, and interface needs of the system. An open system architecture design will specify a particular computer architecture and also provide input/output (I/O) expansion capability using a known interface standard.

### Portable Maintenance Aid (PMA)

The PMA may or may not be part of the CBM data-monitoring and data-collection effort. In more sophisticated CBM systems, the PMA runs an IETM that uses the PMA to connect to the embedded data bus and extract sensor information to aid the troubleshooting process. The PMA links to the off-board (or analytic) part of the CBM system to download troubleshooting and/or "health check" information to the database and trend analysis system.

The computer architecture of the PMA is most often based on a popular portable PC architecture, such as Intel or Apple, and, more recently, the Palm handheld devices. This practice significantly lowers acquisition costs, though it places a burden on the systems integrator to address "ruggedization" features.

### Off-Board Computerized Maintenance Management System (CMMS)

The off-board part of the CBM system is typically a networked workstation environment using the Ethernet (IEEE 802.1) standard. One computer generally acts as the interface to the embedded/PMA components, while the database resides on another computer somewhere on the network and operates in a shared environment.

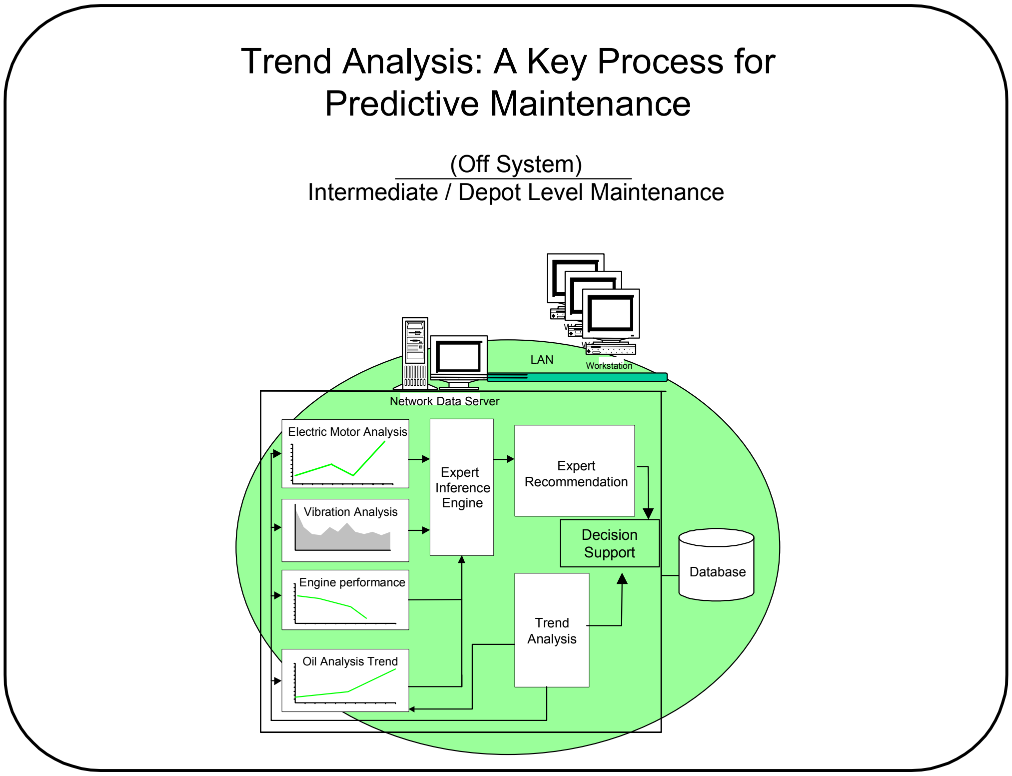
On the industrial side of CBM and CMMS, suppliers typically address these standards in their product offerings.

### Turn-Key CMMS Solutions

The commercial CBM industry provides a range of system solutions, from individual software packages to complete turnkey systems. The Navy's ICAS system is an example of a CBM system that started as a turnkey package of sensors and an off-board CMMS system and gradually added capabilities from a base platform.

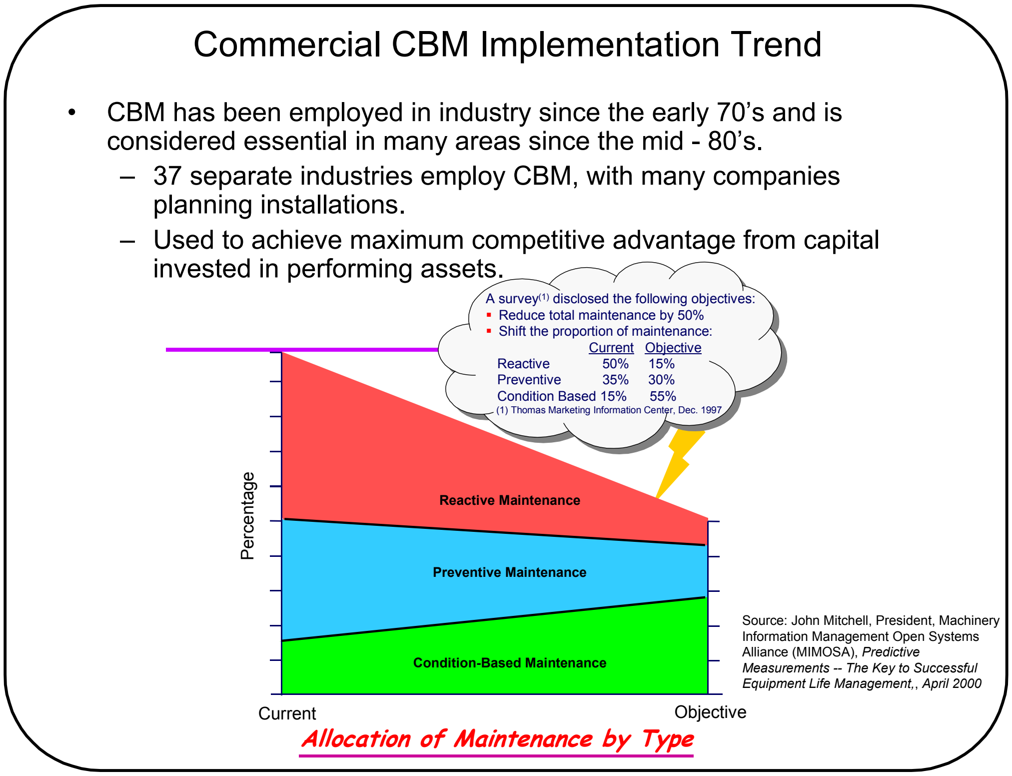
## DATABASE

The database is a key area for open standards; it is typically addressed when selecting the supplier of the database management system. The rise of Internet functionality and web-enabled commerce supply chains is creating a new generation of database concepts that may soon replace the traditional database suppliers. These are all based on open Internet standards, and will create a new dimension for $C^4I$ systems architecture.




# Trend Analysis: A Key Process for Predictive Maintenance

Trend analysis uses off-board computing powers to collect and analyze data from many weapon systems. Database requirements can be huge, but this potential hardware risk element to a CBM system design is mitigated by the substantial decline in the prices of mass storage density. Trend analysis software can operate not only on a single weapon system, but on a fleet as well, and can use fleet-wide information to improve trend analysis. Trend analysis and expert recommendation software are two different things; both need to operate on the same data and support decision logic for failure prediction. We will discuss trend analysis limitations in a later section.




# Commercial CBM Implementation Trend

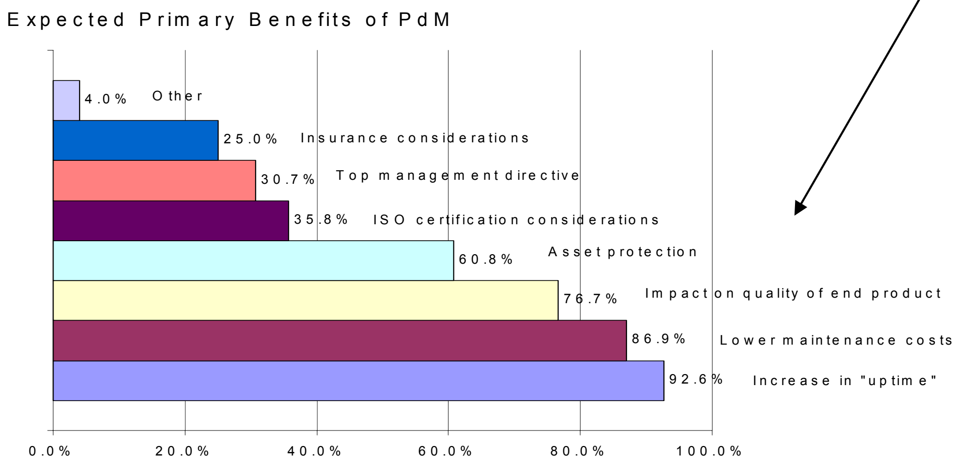
It is important to briefly review the commercial-industrial CBM environment because of the greater maturity of implementation efforts in the private sector than in the public sector. The transition to CBM in industrial applications is proceeding from a much richer base of experience than military programs have, providing a potential wellspring of lessons learned for military programs.

CBM practices have penetrated almost every type of major commercial factory/distribution environment. The industrial arena for CBM is much larger than that of the military, and represents the bulk of progress made in CBM technology and CBM implementation effectiveness.

The progression toward CBM in industry is not yet complete, as the above chart shows. The objective in industry is to achieve much higher levels of CBM employment than exist today. But industry goals are much the same as military goals, as the next chart shows.

## Industry Goals for CBM

- Primary industry goals for CBM and predictive maintenance* are similar to military goals:
  - Lower Maintenance Costs
  - Increase Equipment Uptime




* PdM = Predictive Maintenance

Source: Keith Mobley, *PLANT SERVICES MAGAZINE*, April 2000

# Industry Goals for CBM

This chart reflects that a very high percentage of users have expectations for increased uptime and lower maintenance costs. Both of these goals are also drivers for military maintenance programs considering CBM and prognostic programs.

A CBM infrastructure has been built over time in the commercial sector that helps guide its effective employment and promotes sharing of information across industries. This infrastructure represents a set of resources for military programs to build upon in their own CBM programs.

Being able to capitalize on the richness of the commercial CBM sector infrastructure is one of the principal reasons to design weapon system and associated CBM programs on an open architecture basis.

Commercial CBM Infrastructure

- **Industry Consortium**
  - MIMOSA - Machinery Information Management Open Systems Alliance
- Academic Centers Of CBM Research
  - The University of Tennessee's Maintenance and Reliability Center
  - Pennsylvania State's Advanced Research Laboratory
  - Texas A&M University's Turbomachinery Laboratory
- Professional Societies
  - The Society for Machinery Failure and Prevention Technology
  - The Society of Maintenance and Reliability Professionals
  - The Vibration Institute
  - The Society of Automotive Engineers (SAE)
  - International Standards Organization (ISO)
- Trade Publications
  - Maintenance Technology Magazine
  - Reliability Magazine
  - Plant Services Magazine

## Commercial CBM Infrastructure

The commercial machinery sector has an open-systems forum comprised of a consortium of companies that use or supply CBM technology—Machinery Information Management Open Systems Alliance (MIMOSA). MIMOSA is comprised of over 50 companies that participate in an open-exchange of ideas and practices. Substantial benefits are available to the Services and their suppliers by joining MIMOSA. This could promote a beneficial exchange among all parties, ensuring that MIMOSA open standards reflect Service requirements for CBM and other predictive maintenance applications. For example, it was noted at a recent CBM symposium that requirements for exchanging shipboard maintenance information could be included in MIMOSA's open conventions and protocols.[2]

A number of universities sponsor centers focused on reliability, machinery diagnostics or CBM. Generally, these centers are integral to the universities' engineering departments.

In the commercial sector, there are professional societies that focus on condition-monitoring and professional journals and periodicals dedicated to examining technology, applications and economic considerations in CBM and other maintenance concepts. A wide range of articles provides relevant information pertaining to CBM technology and business case discussions.

[2] *Comments on Equipment Life Cycle Management*, John Mitchell, July 1998, presented at ASNE-98 CBM Symposium sponsored by NAVSEA04M.

## Commercial CBM Infrastructure (Continued)

- Conferences
  - Industry/Academia sponsor key conferences
    - e.g., <u>The 53d Meeting of the Society for Machinery Failure and Prevention Technology</u>
- Best Manufacturing Practices Center of Excellence Web Site (**http://www.bmpcoe.org**)
  - Partnership among:
    - Office of Naval Research
    - Bureau of Export Administration, Dept of Commerce
    - University of Maryland's Engineering Research Center
  - Covers Predictive Maintenance, Reliability-Centered Maintenance and other maintenance topics.

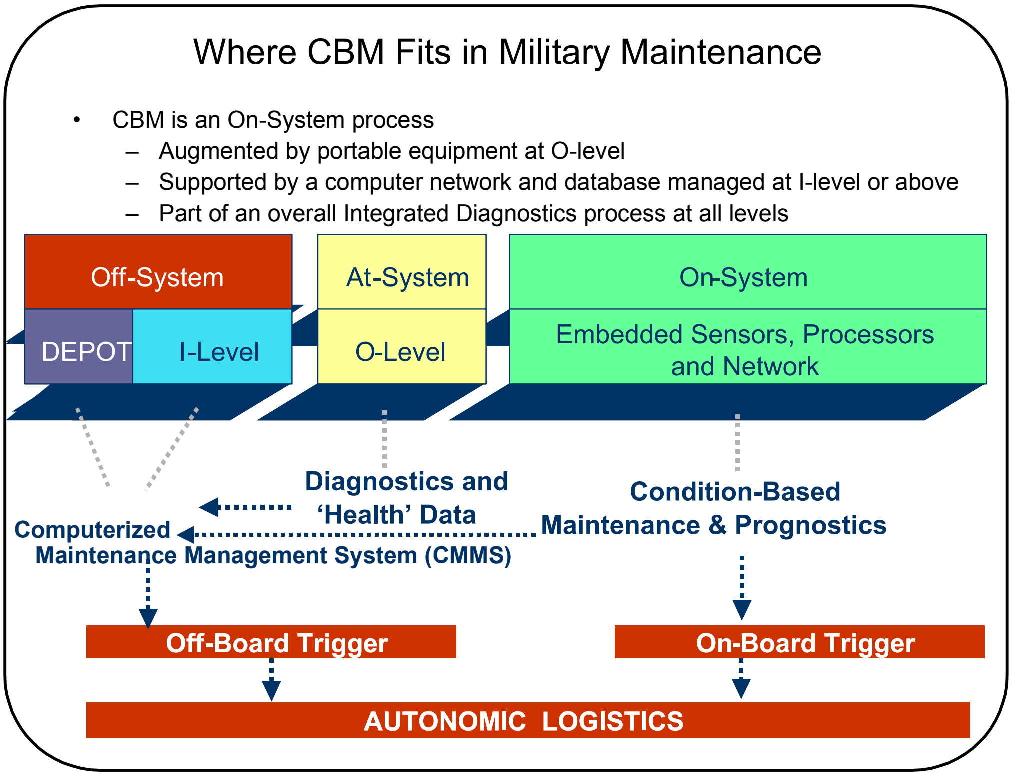
### INDUSTRY CONFERENCES

Corporations, professional societies, and universities sponsor many conferences and symposiums on CBM and machinery diagnostics. Some of these have effective Service participation. For example, at the 53rd meeting of the Society for Machinery Failure and Prevention Technology, both the Navy and the Army Research Laboratory presented papers. Continued, and perhaps expanded, participation may be appropriate as the Services move toward increased implementation of CBM concepts. These forums are important to Service CBM program managers and to decision-makers or program engineers who help craft CBM processes.

### BEST MANUFACTURING PRACTICES WEB SITE

There is a joint venture among academia and government that represents another resource for military maintenance. The Best Manufacturing Practices Center of Excellence (BMPCOE) formed a partnership among the Office of Naval Research, the U.S. Department of Commerce's Bureau of Export Administration, and the University of Maryland's Engineering Research Center chartered to strengthen the U.S. industrial base. The BMPCOE's web site includes surveys of best practices on predictive maintenance and other maintenance topics.[3]

[3] http://www.bmpcoe.org/, Welcome section.




## Where CBM Fits in Military Maintenance

### Maintenance Levels

Military use of CBM must fit within the context of each Service's maintenance doctrine. Although each Service uniquely defines what is accomplished at each level of maintenance, the maintenance level hierarchy itself is similar, with unit (organizational - O), intermediate (I), and depot (D) levels. Evolving maintenance doctrine, with a CBM boost, is blurring the distinction between O and I levels and between I and D levels.

### CBM Starts with Technology Embedded on the Equipment

CBM, as it is being applied to military equipment, is built around sensor and computer technology that can be embedded on the equipment (weapon system) itself, which is monitored both remotely from a distance and directly at the system by portable equipment. In prognostic applications, which are at the high end of CBM complexity and sophistication, embedded computers may directly interact with the logistics system via radio or satellite communication.

### Portable Equipment at O-Level

In the past, portable test instruments have been used for diagnosing immediate problems. In a CBM application, portable instruments are still used as diagnostic tools, but also are used to collect system "health" data from sensors and to transfer that data to the networked maintenance workstation environment which interacts with the logistics system.

### Computerized Maintenance Management System

In peacetime, CBM data flows to the off-board workstation environment that is hosted at the Intermediate level of maintenance. The commercial terminology for this setup is a "Computerized Maintenance Management System." The question of where this capability will work in a wartime environment is a matter still under doctrinal evaluation.

### Autonomic Logistics

Each Service is developing a concept for anticipatory maintenance, to use the term in JV2010's Focused Logistics section. Each service has a different name for it, and each defines different functionality and goals, but they are all concerned with essentially similar concepts.

The JSF calls this Autonomic Logistics. The concept is tied to the functionality in the JSF PHM system. Autonomic Logistics concepts are to reduce maintenance manpower requirements by up to 40 percent, increase combat sortie generation rate by 25 percent, and reduce the logistics footprint (in terms of C-17 cargo aircraft loads) by 50 percent, all relative to current strike aircraft.[4]

The components of autonomic logistics are:

- A highly reliable, maintainable, and intelligent aircraft that incorporates a prognostics and health management capability
- A technologically enabled maintainer
- A Joint Distributed Information System (JDIS) that incorporates technology to provide decision support tools and an effective communication network linking the JSF with the logistics infrastructure
- A logistics infrastructure that is sufficiently responsive to logistics needs within a timescale which allows the JSF weapon system to deliver effective sorties at required rates in the most cost-effective fashion.

The JSF Operational Requirements Document (ORD) specifies the functionality to accomplish autonomic logistics.

[4] http://www.jast.mil/html/phm.htm.

Major CBM Programs in the Services

- New System Design
  - **JSF PHM**, Joint Strike Fighter Prognostic Health Management

- Application to Legacy Equipment
  - Navy **ICAS**, Integrated Condition Assessment System (NAVSEA)
  - Army **ADIP**, Army Diagnostic Improvement Program
  - Helicopter **IMD HUMS**, Integrated Mechanical Diagnostics, Health Usage & Monitoring System

## Major CBM Programs in the Services

We reviewed the following four programs, considered strategic programs, based on their size and scope:

- Joint Strike Fighter Prognostic Health Management (JSF-PHM)
- Navy Integrated Condition Assessment System (ICAS)
- Army Diagnostic Improvement Program (ADIP)
- Integrated Mechanical Diagnostics, Health Usage & Monitoring System (IMD-HUMS), a helicopter CBM program

The JSF is a new design weapon system, just completing concept development. JSF PHM represents what can be done with current technology when weapon system design and CBM design go hand-in-hand. The other programs address improved CBM capabilities for legacy weapon system fleets.

We will examine the four programs using the templates of functions and features for comparative evaluation. We describe the operational concept in simplified terms to facilitate comparison of basic program concepts, and we also show a similar block diagram for each program which identifies the major components and how the programs differ at this level.

Program Assessment

- Each Service program is different from the others
  - Scope
  - Time Horizon
  - Goals
  - Technology
  - Linkage to Logistics Support

- Each Service program has some points of excellence the others do not have
  - Best Practices

## Program Assessment

Each program selected for review in this report differs from the others in a number of ways. This variation facilitates a broader perspective of the issues involved in the development and implementation of CBM. Each program has a broad scope, either from a time, funding, or weapon system perspective, making each what we consider to be a strategic program versus a technology development effort, or a program that may be limited in application to a single weapon system.[5]

### CBM Linkage to the Logistics System

As in CBM technologies, wherein vibration monitoring turns out to be a key predictive technology, there are certain CBM program capabilities that give CBM maximum impact from the standpoint of achieving Joint Vision 2010 goals. Many aspects of CBM create cost economies, but unless there is a direct relationship between predictive maintenance and the logistics response, mission-related improvement goals of CBM may not achieved.

To support desired improvements in logistics velocity (i.e., to speed up logistics response time), there must be a logistics link from CBM to the Service logistics information system. If the issue is logistics velocity that enables faster weapons

[5] There are many worthy CBM projects we will not review in this report, as they focus on weapon-system specific applications. These include, for example, the condition monitoring capabilities on Navy aircraft such as the E-2C, F-14 and F/A-18.

system turnaround time, either from a repair or sortie generation standpoint, then the more real-time the communication link to the logistics support system, the faster the potential weapon system turnaround, and therefore the better the operational availability over time. In this regard, we think of turnaround in terms of aircraft sortie generation rates or mean-time-to-repair and return fighting vehicles to combat.

Not all CBM programs directly address the logistics linkage issue, making this capability a key program discriminator. Ships don't fit well with the concept of fast turnaround from a whole-ship standpoint, but they certainly fit well with this concept at the weapon system level, such as an Aegis missile or a ship defense system.

## Review Format

We look at each of the CBM programs selected with a set of five charts, each of which was described in detail earlier:

- general descriptive summary
- graphical view of the concept for CBM
- functional block diagram
- on-board and off-board capabilities
- diagnostic/prognostic functionality.

After looking at each of these programs individually, we summarize the key points of each program in a set of charts laying out a side-by-side comparison.

## Best Practices

We follow that with a summary chart of best practices, the full amplification of which is the subject of another report, and conclude with key issues.

## JSF-PHM Overview

| | Program Description |
|---|---|
| | JSF-PHM |
| Time horizon | 1997–2037 |
| Type of program | Phase I: Concept exploration, technology maturation & risk-reduction; entering Phase 2 (competitively selected), Engineering and Manufacturing Development (EMD) in 2001 |
| Scope of program | USAF & RAF air-air, air-gnd; USMC STOVL; Navy carrier aircraft |
| Program goals | To enable autonomic logistics, and through that, to maximize sortie generation rates and mission reliability, to reduce the logistics footprint and to eliminate false alarms |
| | |
| Technology | |
| On-Board H/W | Sensor, actuator and microprocessor intensive environment, tailored for PHM |
| On-Board S/W | Hierarchy of prognostic software reasoning systems |
| COTS Technology | Microprocessors, interfaces to information systems |
| Open-Systems Architecture | Yes |
| Logistics Linkage | Triggered by on-board prognostic software |

# JSF-PHM Overview

The JSF PHM system is an intellectual process leader driving many of the innovations in prognostics, from raw technology to software architecture to open systems integration. Its time horizon spans a forty-year period, from the beginning of concept exploration to projected retirement after a thirty-year service life.

### Intellectual Leadership

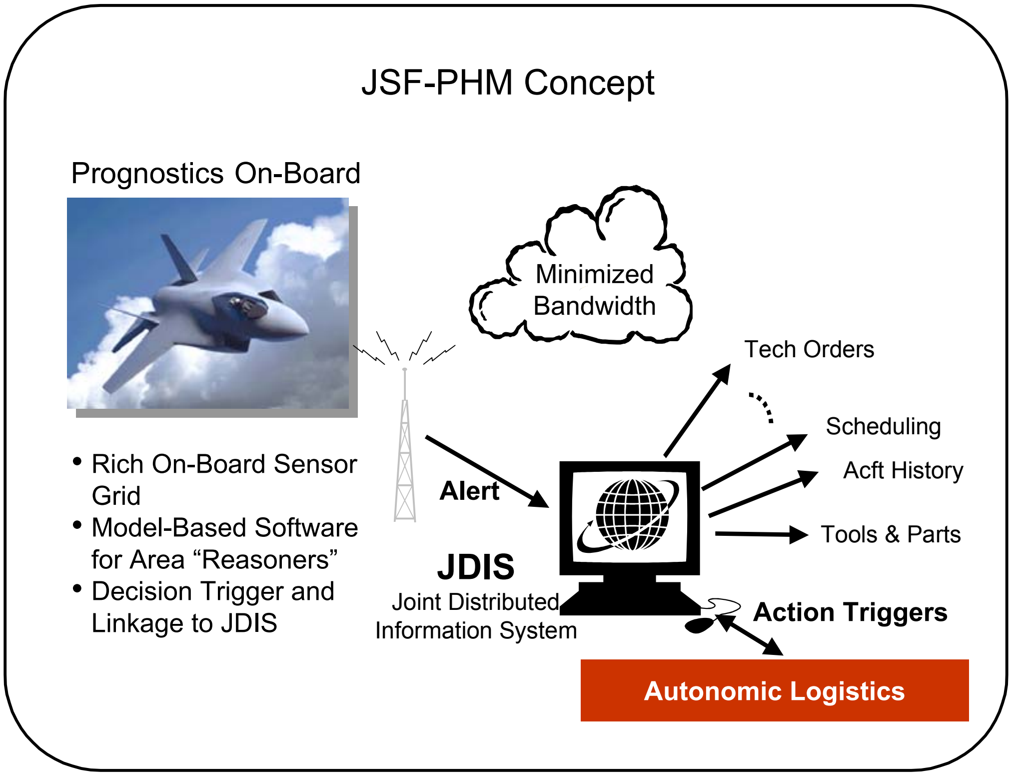
The JSF PHM program concept and its emerging implementation show what is possible in CBM technology, prognostic functionality, and logistics response. The program has seeded many technical and systems integration advances. It is premised on the integration of multiple commercial technologies and addresses information systems integration across three services (USAF, USN and USMC), as well as the United Kingdom's Royal Air Force, a co-development partner with the United States. Key to comprehending the impact of the JSF PHM program is to understand that it is intimately tied to rapid logistics response through what the program calls autonomic logistics, as described earlier.

### Prognostic Health Management

The PHM approach provides advanced on-board diagnostics and testability. It fully enables on-condition maintenance and triggers system reconfiguration in flight. The approach also triggers the autonomic logistics support aspects of the JSF PHM concept.

### Impact on Legacy Systems

The PHM program is impacting legacy weapon systems across DoD for two reasons. One is the broad scope and composition of the two prime contractor teams competing for the main aircraft development contract. The other is that some of the PHM technologies have a broad appeal across system commodities. The teams form a showcase of aerospace and defense contractors, such as Boeing, Lockheed Martin, British Aerospace, Honeywell, Raytheon, and IBM, all of which have a fan-out to support contracts on legacy equipment in all the Services. For a fan-out perspective, one can take any major subcontractor and map its prime programs to see where JSF PHM concepts are moving. From a technology perspective, oil debris monitoring is a good example of technology maturation moving to other programs, as it migrates from the JSF program to the helicopter HUMS programs and, eventually, to ground systems.

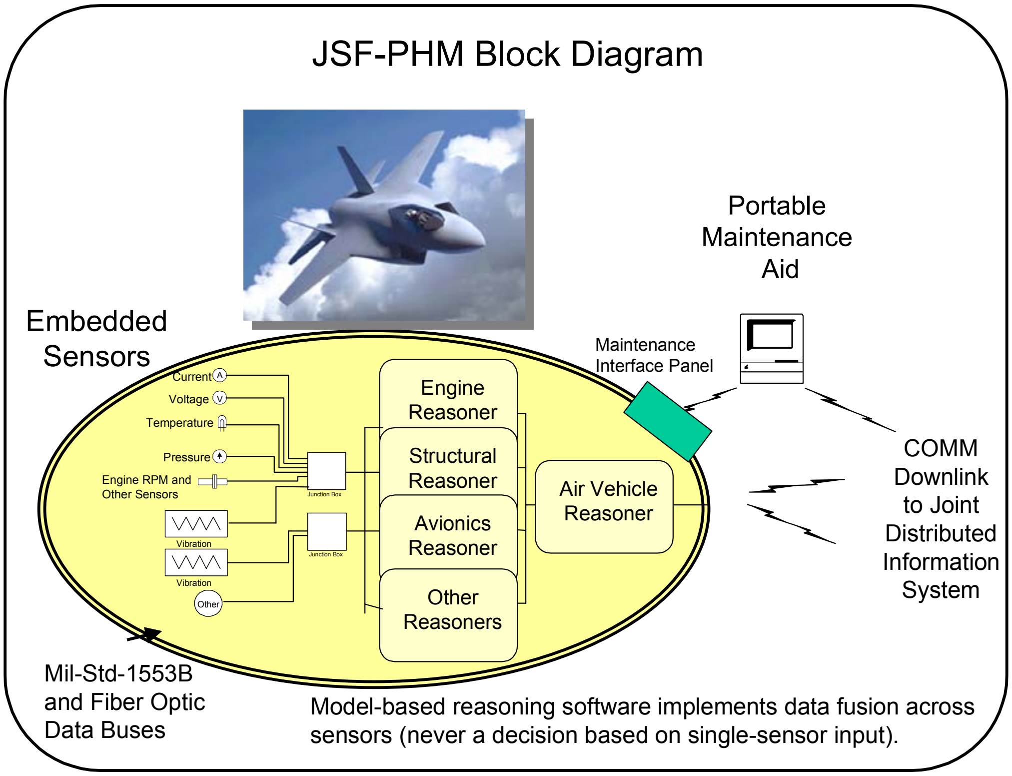



# JSF-PHM Concept

The JSF PHM concept is built around the ability to diagnose or predict a failure on-board, assess it on-board, and communicate the assessment to the logistics support infrastructure in real time for immediate corrective action. The logistics infrastructure is postured to being able to respond automatically to alerts or triggers from the aircraft, so that as an aircraft returns from a mission, it may be met at the airfield with whatever is needed to turn the aircraft around as fast as possible. PHM is not simply a monitoring program, which is why it's termed a health management process by Dr. Bill Scheuren, Advanced Technology Director of the JSF program. Through Joint Distributed Information Systems (JDIS), PHM takes positive actions to address and correct predicted failures before they affect aircraft mission performance.

Because PHM assesses failures and attempts on-board in-flight work-arounds, it affects the current mission of the aircraft as well as future missions.

JDIS—a JSF-initiated concept—is the key to making PHM and autonomic logistics concepts work. Built into JDIS are the decision support processes necessary to track asset visibility from the original equipment manufacturer (OEM) to the aircraft, as well as the complete history of individual aircraft and the entire aircraft fleet. If a maintainer needs certain technical instructions, parts and tools, JDIS will coordinate that; so JDIS is much more than an interface to the logistics information system—it is the heartbeat of the system. JDIS is the mechanism that makes autonomic logistics work. It is the hub of all maintenance and logistics activities.




# JSF-PHM Block Diagram

The key to JSF PHM on-board prognostics capability lies in the sophisticated network of sensors, and, even more important, in the software architecture that draws on the sensor data and "reasons" about the nature of what it knows.

## THE SOFTWARE REASONING SUBSYSTEMS

The software reasoner architecture is partitioned along the same lines as the major aircraft subsystems, such as avionics and propulsion. Each diagnostic reasoner is built on a model of the functionality of that subsystem. Thus it can make inferences about the operation of the subsystem, based on key inputs from sensors and actuators in that subsystem. It can also infer subsystem health from points that are not sensored, based on knowing through the model about conditions that can be generated or passed on from other subsystems.

A key tenet of the reasoning system is that it will not attempt to make inferences from a single sensor input, thereby creating the basis for increasing forecasting confidence by drawing on knowledge from other areas at the air vehicle reasoner.

## THE DATA BUS

As we mentioned earlier, the data bus is a key open systems architecture enabler as well as being key to exchanging digital information both on and off-board. The JSF PHM system utilizes the Mil-Std-1553 data bus for its message traffic, as well as a fiber-optic data bus. All data buses on the JSF are dual-redundant, so certain failures can be assessed and mitigated on board.

## PHM System Uniqueness

No other weapon system now in the field or in development contemplates this kind of sophisticated on-board health management system, though the helicopter Health Usage and Monitoring System (HUMS) comes closest.

JSF-PHM On-Board / Off-Board Capabilities

| On-Board | | | | | |
|---|---|---|---|---|---|
| Condition Monitoring | Data Collection | Communication | Reasoning | Event Detection and Isolation | Logistics Alert Trigger |
| ● | ● | ● | ● | ● | ● |

| Off-Board | | | | | |
|---|---|---|---|---|---|
| Condition Monitoring | Data Collection | Communication | Reasoning | Event Detection and Isolation | Logistics Alert Trigger |
| ● | ● | ● | ● | ● | ● |

# JSF-PHM On-Board / Off-Board Capabilities

The JSF PHM system's broad-spectrum capabilities cover all of the on-board and off-board CBM system features. It is the only weapon system that does so.

The JSF aircraft communication subsystem utilizes both over-the-horizon (OTH) radio and satellite means for long-distance communication. The PHM system is allocated some of that bandwidth and will use it for both on-condition-reporting and reporting at fixed times in flight.

JSF-PHM Diagnostic / Prognostic Functionality

| Functions | JSF PHM |
|---|---|
| Fault Detection | ● |
| Fault Isolation | ● |
| Fault Prediction | ● |
| Fault Recovery | ● |
| Fault Assessment | ● |
| Fault Reporting | ● |
| Sensor-Coupled IETM | ● |
| Logistics Trigger | ● |

# JSF-PHM Diagnostic/Prognostic Functionality

The JSF PHM system maps across the complete spectrum of our table of diagnostic/prognostic functions–again, the only weapon system health management system to do so.

All CBM programs and the weapon systems and equipment they support can detect faults and, to some degree, predict faults. They all report faults and usage in terms of hours or miles. But no other program precisely isolates the fault while the system is in operation. The capability to isolate precisely leads to an ability to assess the fault or failure for its impact on the current mission. From this assessment capability comes the ability to potentially recover from faults, re-route required connectivity (e.g., use alternate data paths), or operate with some level of known degradation. All of these options are a work-in-progress for the JSF aircraft and the PHM subsystem.

Fault isolation that can not be accomplished on board, or that requires corroboration off-board before making a maintenance task decision, is accomplished through the use of a PMA. The PMA can download portions of the relevant technical order applicable to the particular job, and then can interface with the aircraft PHM reasoners through the Maintenance Interface Panel (MIP) or via wireless means.

ADIP Overview

| | Program Description |
|---|---|
| | ADIP |
| Time horizon | 1998 – 2005 |
| Type of program | Legacy systems |
| Scope of program | All combat vehicles, missiles and aircraft; all support vehicles and aircraft; all mobile electric power |
| Program Goals | Reduce NEOF by 50 percent |
| | Reduce O&S costs by 20 percent |
| | Reduce life cycle costs for all systems |
| | Redesign the diagnostics business process to establish an electronic link from the weapon system to the GCSS-A |
| | |
| Technology | |
| On-Board H/W | Diesel powered vehicles using SAE std data bus and sensors; engine/trans/ABS control units (ECU) as designed by commercial vehicle OEMs |
| On-Board S/W | Diagnostic messages generated by the ECUs |
| COTS | Data bus, sensors, ECU, message protocols |
| Open-Systems Architecture | Yes |
| Logistics Linkage | Triggered by off-board statistical analysis |

# ADIP Overview

ADIP is aimed at improving the diagnostics and prognostics of all Army weapon systems and equipment by the application of common technologies across multiple systems. ADIP addresses all Army commodities and systems. In fact, it addresses more types of equipment than any other Service program and is the broadest in scope of DoD's legacy equipment maintenance improvement programs.

ADIP has three time-phased "thrusts" grouped according to the time frame required for implementation. The Program Manager for Test, Measurement, and Diagnostic Equipment (PM-TMDE) oversees the program through a series of integrated product teams whose membership is drawn from equipment program manager (PM) offices and Army staff agencies. The three thrusts are:

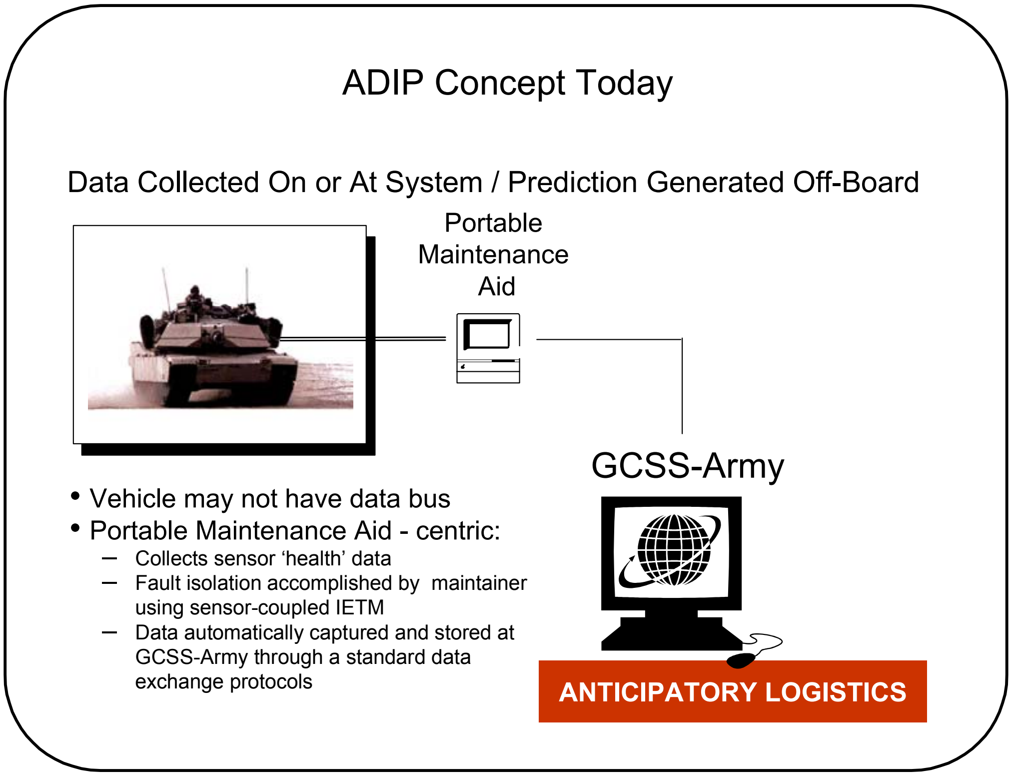
- Short-term - immediate technology insertion programs to improve diagnostics
- Mid-term - to develop anticipatory maintenance capability in ground vehicles and helicopters
- Long-term - to develop an embedded diagnostics proof-of-concept for a common architecture and approach (similiar to the JSF PHM embedded architecture design goals).

## Background

The ADIP predictive maintenance concept originated in diesel-powered vehicles, including: trucks, self-propelled artillery howitzers, the Bradley fighting vehicle, engineer vehicles such as tank retrievers, bulldozers and construction equipment, mobile electric power generators, and watercraft. The equipment scope of ADIP CBM employment, particularly when Army gas turbine helicopters are added in, is by far the largest and most diverse application environment in DoD.

Most diesel engines come from three engine manufacturers, Detroit Diesel, Caterpillar, and Cummins. These engine manufacturers are driven by requirements from commercial needs; less than 10 percent of their business is from military orders. The biggest technology driver in commercial engine design is meeting Environmental Protection Agency emissions standards. Meeting these standards has propelled the rise of the electronically controlled diesel engine, with its sensors and digital engine control units. The SAE has specified a standard means for exchanging on-board engine and drive train data via a standard data bus. ADIP, therefore, was born of COTS technology with open architecture roots. This gives ADIP an immediate focus on preserving that emphasis as the numbers and types of equipment that employ its concepts expands.

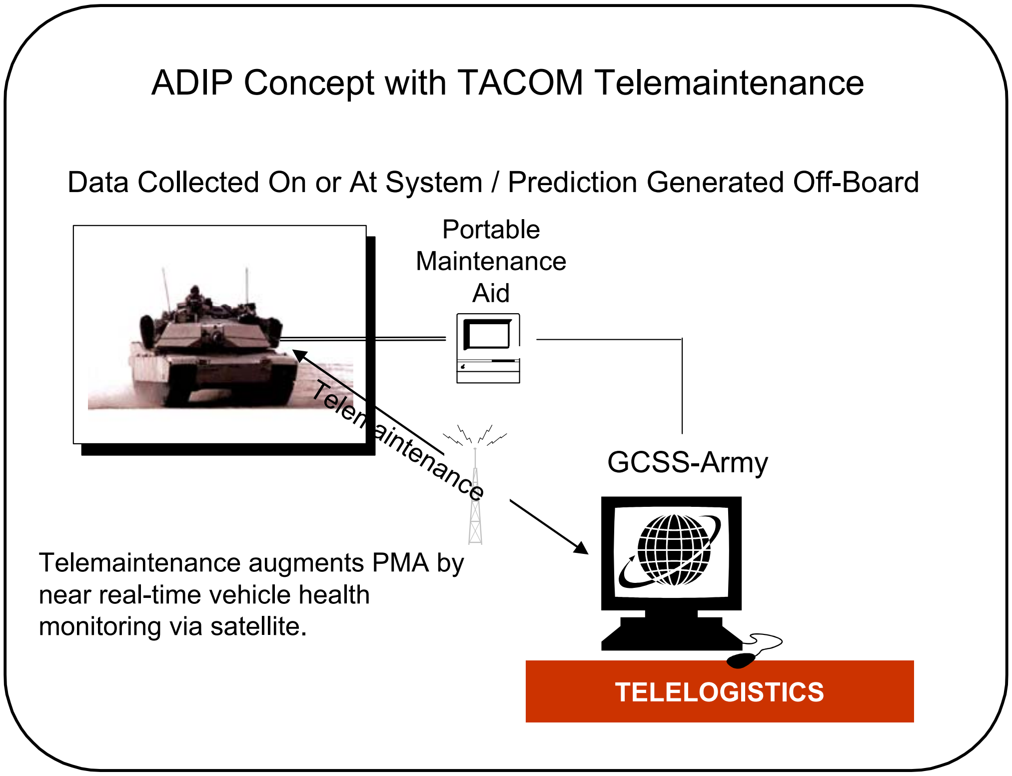
The ADIP vision and program are managed by PM-TMDE, supported by extensive collaboration with the Army Logistics Integration Agency (LIA), the PM for Global Combat Support System-Army (GCSS-Army) and various weapon system PMs. The first major CBM initiative by PM-TMDE (preceding ADIP in the early 1990's and giving rise to it) was the sensor-coupled IETM. The SAE data bus provided access to the sensor and vehicle health information available for vehicles that were equipped with new electronically controlled engines; this facilitated the operation of the sensor-coupled IETM. Collecting the sensor data and the IETM step-by-step troubleshooting data, and saving that data for historical trend analysis led to current ADIP with its three-phased approach. Long-term plans are to develop an embedded, open-architecture prognostic system that interacts with GCSS-Army in much the same way JSF PHM is building its system now.




# ADIP Concept Today

The ADIP CBM concept today is to access on-board data using the PMA as the primary data collection and communication tool. The PMA runs sensor health checks, and the sensor-coupled IETM automatically collects the data and transmits it to GCSS-Army.

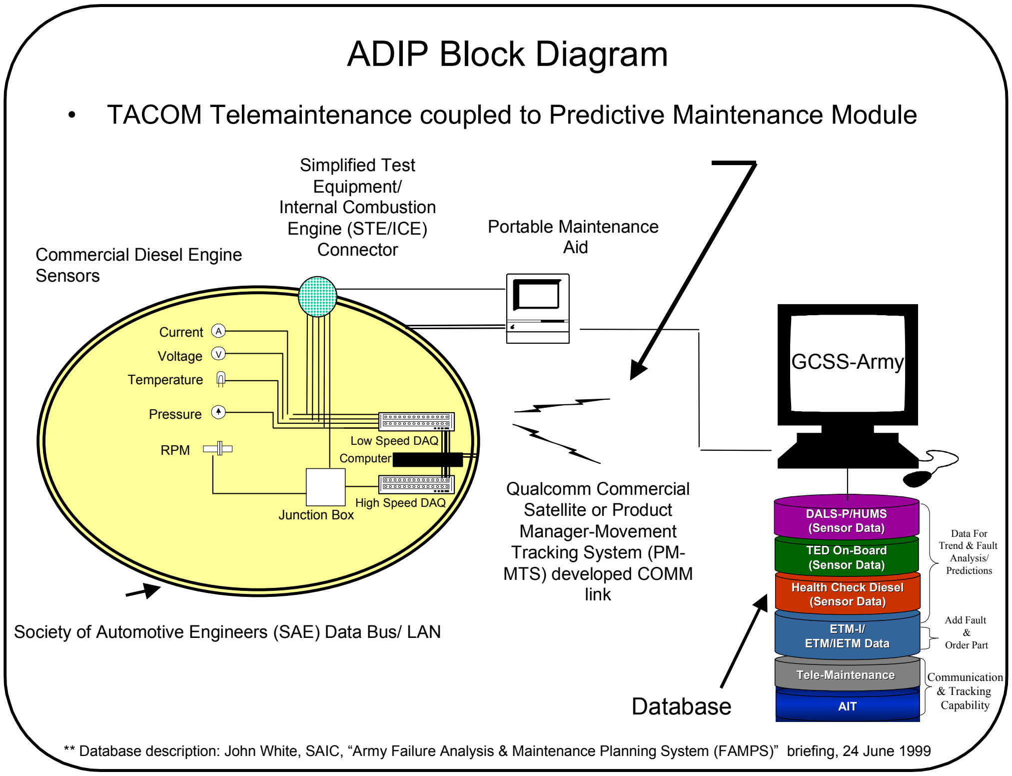
PM-TMDE and PM-GCSS-Army have jointly developed software interfaces to GCSS-Army that apply to IETM data capture and to vehicle health data.




## ADIP Concept with TACOM Telemaintenance

Telemaintenance, which means collecting of on-board vehicle health data and transmitting it via long-range communication media to a maintenance support center for analysis, is under development by the Tank-Automotive and Armaments Command (TACOM) in Detroit. LIA is funding and supporting TACOM in this effort.

Like JSF's autonomic logistics, Telemaintenance supports Telelogistics by linking the maintenance center and/or the individual vehicle to the logistics system through the maintenance center. At TACOM, the Electronic Maintenance System (EMS) handles the sensor-coupled IETM and the PMA collection of vehicle sensor health data. EMS integrates the resulting information into the logistics system and enables real-time tracking of vehicles and weapon systems and their maintenance status.




# ADIP Block Diagram

The on-board hardware components of ADIP are COTS, delivered as a package by the engine, transmission and other vehicle subsystem OEMs, and integrated into the vehicle by the vehicle OEM.

## EMBEDDED SENSORS

Sensors in Army vehicles come in two distinct forms, those on mechanically controlled engines and those on electronically controlled engines. The older mechanical engines are being phased out of Army and U.S. Marine Corps (USMC) inventory as part of vehicle remanufacturing programs, such as the USMC Medium Tactical Vehicle Replacement program, or new vehicle development, such as the Army Family of Medium Tactical Vehicle program. Vibration sensors are not presently in the Army suite of sensors used for CBM purposes as commercial diesel engine OEMs have not provided them.

## PMA FUNCTIONALITY FOR CBM

The PMA reads the vehicle sensors either directly via a common multiple-pin connector, or by connecting to the data bus and capturing the data from sensors that have been processed by the on-board engine control unit. The PMA collects the sensor data through a stand-alone process known as a health check, or it selectively interrogates only those sensors appropriate to a troubleshooting session for a known symptom, using the sensor-coupled IETM.

## GCSS-Army Interface and Interaction

One of PM-TMDE's major CBM initiatives has been the development of the Predictive Maintenance Module (PMM), previously known as the Failure Analysis and Maintenance Planning System (FAMPS). This is essentially a database capability for collecting, storing, analyzing and acting on equipment condition trends identified in the data. There is a high degree of collaboration with PM-GCSS-Army and its Army Combined Arms Support Command (CASCOM) parent. This sets the ADIP program apart from other CBM system developments, given the extent and nature of the interfaces developed and the modifications made to the GCSS-Army information system to support predictive maintenance functionality.

## Database

The Army database[6] that stores and analyzes vehicle health data contains many separate compartments of vehicle health information. As a result, the database is structured to facilitate individual weapon system capabilities in health data collection. For example, separate data definitions are provided for TED (Turbine Engine Diagnostics), a program apart from ADIP, but for which ADIP makes provisions for incorporation into the GCSS-Army PMM.

The power of the predictive nature of the system is extended by correlation with geographic and weather data, which is collected from NOAA, the National Oceanic and Atmospheric Agency, and stored in the GCSS-Army data base. This data can then be used to determine, for example, environmental impacts on equipment degradation and maintenance requirements.

[6] Database description: John White, SAIC, "Army Failure Analysis & Maintenance Planning System (FAMPS)" briefing, 24 June 1999.

**ADIP On-Board / Off-Board Capabilities**

| On-Board | | | | | |
|---|---|---|---|---|---|
| Condition Monitoring | Data Collection | Communication | Reasoning | Event Detection and Isolation | Logistics Alert Trigger |
| ● | ● | ◐ | ○ | ○ | ○ |

| Off-Board | | | | | |
|---|---|---|---|---|---|
| Condition Monitoring | Data Collection | Communication | Reasoning | Event Detection and Isolation | Logistics Alert Trigger |
| ● | ● | ◐ | ● | ● | ● |

Note: Communications capability attributed to TACOM telemaintenance functionality.

## ADIP On-Board / Off-Board Capabilities

As mentioned in the last slide, the sensor and computer hardware embedded in Army ground vehicles equipped with electronically controlled engines is COTS technology supplied by OEMs. Currently, ADIP has no embedded diagnostic reasoning on board and, therefore, no decision support process. Phase three of ADIP—the long-range plan—addresses that capability.

As presently configured, ADIP captures on-board data and transmits it to GCSS-Army for statistical analysis and data-mining for detecting and predicting impending failure events. Since this process is integral to GCSS-Army, the logistics support decision trigger is also built into the system.

PM-TMDE handed off the sensor-coupled IETM refinement process to TACOM after proof-of-principal development was completed in 1996. Since that time, TACOM has been extending sensor-coupled IETM use on its tactical and fighting vehicles and extending the technology to include real-time long-distance communication links. Initial telemaintenance concept development was demonstrated in 1997 using a Qualcomm commercial satellite. The telemaintenance software architecture provides for multiple communication media, including cellular and packet data methods. A USMC telemaintenance variation was also built and demonstrated in early 1997, using the sensor-coupled IETM for a USMC Palletized Load System (PLS) truck, communicating via a USMC TRC-170 troposhperic scatter radio as the long-distance communication medium.

PM-TMDE will integrate telemaintenance communication with GCSS-Army using the standard Army $C^4I$ system.

ADIP Diagnostic / Prognostic Functionality

| | ADIP | |
|---|---|---|
| Functions | Ground | Helicopter |
| Fault Detection | ● | ● |
| Fault Isolation | IETM | IETM |
| Fault Prediction | ● | ● |
| Fault Recovery | ○ | ○ |
| Fault Assessment | ○ | ○ |
| Fault Reporting | ● | ● |
| Sensor-Coupled IETM | ● | ○ |
| Logistics Trigger | ● | ○ |

## ADIP Diagnostic/Prognostic Functionality

The chart shows both ground systems and helicopter systems. PM-TMDE is managing a separate helicopter HUMS program, which is independent of ADIP, but coordinated with it. Major Army helicopter acquisition programs (e.g., Longbow-Apache, Kiowa-Warrior & Blackhawk) are each developing their own IETMs, none of which is sensor-coupled.

ADIP currently supports basic CBM system diagnostic functionality. Fault detection is an on-board function, but isolating the fault is an O-level maintainer task, supported by the sensor-coupled IETM. Predictive capability is derived by collecting IETM data and sensor health monitoring data, both accomplished using a PMA and storing the data in a database for subsequent trend analysis.

There is no capability for on-board fault assessment or recovery in ADIP.

The TACOM telemaintenance/telelogistics effort extends ADIP to potentially include an on-board logistics trigger (link to supporting logistics systems). We did not assess either this capability or related capabilities in the Army HUMS effort.

## ICAS Overview

| | Program Description |
|---|---|
| | ICAS |
| Time horizon | 1997–2003 |
| Type of program | New ships and Legacy ships |
| Scope of program | All Navy surface fleet ships |
| Program goals | To automate the preparation of the ship logbook |
| | |
| Technology | |
| On-Board H/W | No embedded sensors or computers in older ships. Newer gas turbine-powered cruisers and destroyers have both embedded sensors and data bus. Ship has network of CMMS workstations |
| On-Board S/W | No embedded software, except for systems mentioned above. IDAX CBM software runs on the CMMS network |
| COTS Technology | ICAS system adapted from commercial IDAX application |
| Open-Systems Architecture | ICAS – yes; legacy systems vary |
| Logistics Linkage | Not linked |

# ICAS Overview

Integrated Condition Assessment System (ICAS) is a trademarked commercial product from IDAX, Inc. It has been adapted and modified for use on Navy surface ships. As an adapted COTS product, ICAS is similar to ADIP in that it is firmly rooted in commercial technology.

ICAS is a data acquisition and analysis system comprised of hardware, software, and sensors for monitoring equipment and scheduling maintenance based on equipment condition.

The ICAS goal, funding permitting, is to retrofit major Navy ships (~320) in both the Atlantic and Pacific surface fleets (SURFLANT and SURFPAC respectively). To date, approximately 62 ships have been outfitted with ICAS technology. About half the fleet has old equipment, including propulsion systems which are primarily steam-powered; the cost effectiveness of retrofitting sensor capability is yet to be determined.

Currently, the principal goal for ICAS is to automate preparation of the ship logbook, a manpower-intensive task requiring substantial sailor time. Payback from this initial objective is quantified as manpower savings:

- Automating 45 percent of DDG51 Logs saves approximately 15,000 man-hours annually.

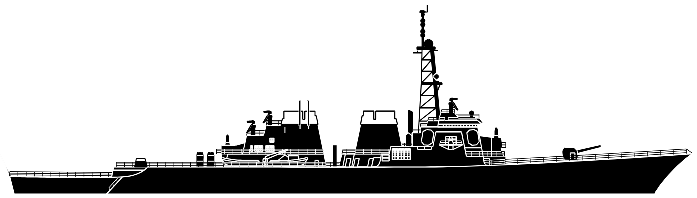
- Automating 30 percent of CG47 Logs saves approximately 11,000 man-hours annually.

- Automating 11 percent of DD963 Logs saves approximately 6,500 man-hours annually.

As fleet command and staff gain confidence in the system, more ambitious objectives will be set. NAVSEA04M has been a visionary agency in outlining next-generation CBM concepts, and SURFLANT has been aggressive in supporting ICAS fielding.

ICAS Concept

**Data Collected On the Ship / Prediction Generated On the Ship**
*A self-contained environment*



- May or may not have data bus
- Sensor coverage varies
- No long-distance communication link at this time
- CBM data shared with Fleet Technical Support Center when ship docks

# ICAS Concept

## OVERVIEW

ICAS is a Microsoft Windows NT-based maintenance program that combines performance-monitoring techniques with computerized maintenance management.[7] ICAS uses graphic diagrams to display machines, systems, and sensors, and monitors and predicts machinery failure modes by comparing on-line, portable, and manual sensor data to established engineering performance criteria. If a machine's actual performance violates a specified limit, an alarm is activated. ICAS automatically logs performance data, stores it in a database folder for future evaluations, and alerts the operator with a visual or audible message.

In addition to signaling the operator during an alarm condition, ICAS provides real-time troubleshooting and diagnostic support to on-scene operators and maintenance engineers. A workstation displays an advisory page that provides guidance for maintenance actions or operating adjustments. These advisory pages can be linked directly with a computerized maintenance management system (CMMS) to generate work orders, work procedures, tools and parts lists, and technical data.

ICAS supports predictive maintenance capability. Machine operating data is logged on a regular basis to develop operating trend information. When a ma-

[7] This overview excerpted and condensed from ICAS Users Manual, Idax, Inc.

chine starts to degrade, graphical representations of the trend information alert operators, thereby providing maintenance managers with the ability to schedule maintenance actions before a failure occurs.

ICAS is completely self-contained on ship. It does not communicate CBM data off-ship, except by data cartridge that is mailed via regular surface mail. It does not use wide bandwidth or long-distance communication.

Keeping ICAS self-contained on-ship diminishes some mission-related Joint Vision goals:

- There is no automated link to the Service logistic information system, which limits the ability to emphasize logistics velocity.

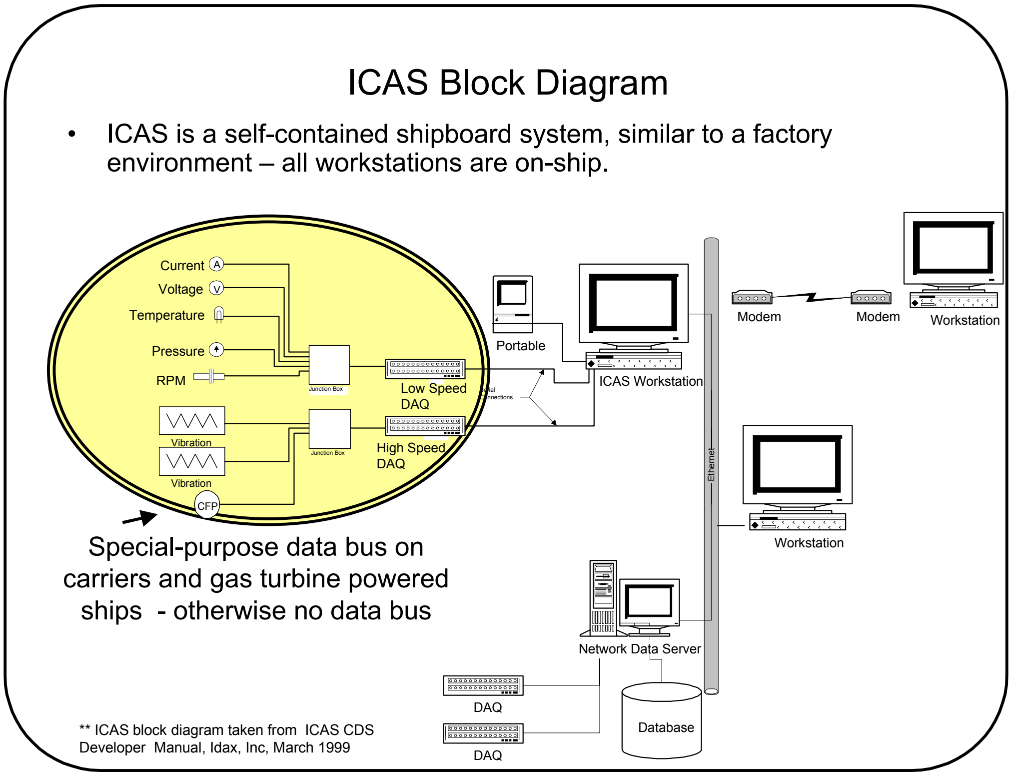
- There is limited advance notice given to on-shore maintenance facilities at Fleet Technical Support Centers (FTSC) to enable assistance on maintenance problems when the ship arrives in port. SURFLANT policy is to mail via surface mail a data cartridge of ship equipment condition data to FTSC. SURFPAC policy is under review.

### Legacy Issues

A map of legacy ship systems technology reflects a wide range of technology, including boiler-generated steam propulsion technology, diesel-electric engines retrofitted from old locomotives, nuclear powered aircraft carriers, and gas turbine-powered cruisers and destroyers. Each ICAS installation requires a significant degree of tailoring to the specific ship environment. ICAS arguably addresses the most difficult legacy retrofit technology issues of all the Services.

### ICAS Plan for the Future

ICAS is planning for shore-based maintenance data sharing via a web-enabled process. It may not have real-time data inputs, but it will be able to perform engineering assessments of shipboard equipment health from remote locations.




# ICAS Block Diagram

ICAS analyzes and trends machine processes and vibration parameters. By maintaining a history of specific machine parameters and comparing them to known standards, ICAS can determine when a machine is beginning to degrade and can alert the machine operator.

ICAS monitors performance indicators on a real-time basis through on-line, portable, or manual sensor inputs. It performs trend analysis based on stored data and can perform broadband and narrowband vibration analysis. ICAS provides a great deal of analytical support to the equipment operator:

- User-defined alarms
- Diagnostic advisories
- Maintenance advisories

Diagnostic advisories are based on fault models and built into the system. Diagnostic advisories assist in diagnosing approaching failures and initiating the restoration process.

Maintenance advisories direct the operator or maintenance engineer through the troubleshooting process. Electronic links are available to provide on-line documentation, including technical manuals, audio-visual procedures, and training materials.

ICAS advisories can be linked with a work management system to automatically schedule corrective or preventive maintenance, though this may or may not be accomplished on a particular ship.

The ICAS workstation network contains large capacity CD-ROM jukeboxes for database management. Presently ICAS doesn’t share ship condition data or information with shore-based locations in real-time or near-real-time modes. Gas turbine-powered cruisers and destroyers use a data bus specified by Boeing, the subsystem contractor.

ICAS On-Board / Off-Board Capabilities

| Embedded | | | | | |
|---|---|---|---|---|---|
| Condition Monitoring | Data Collection | Communication | Reasoning | Event Detection and Isolation | Logistics Alert Trigger |
| ● | ○ | ○ | ○ | ○ | ○ |

| Shipboard | | | | | |
|---|---|---|---|---|---|
| Condition Monitoring | Data Collection | Communication | Reasoning | Event Detection and Isolation | Logistics Alert Trigger |
| ● | ● | ○ | ● | ○ | ○ |

Note: The change in terminology (i.e., on-board/off-board) to embedded – shipboard – more appropriately address ship characteristics.

# ICAS On-Board / Off-Board Capabilities

As currently implemented, ICAS presents a basic CBM system, which performs condition monitoring of surface ship propulsion and hull, mechanical, and electrical (HM&E) subsystems, and passes condition data to a shipboard maintenance workstation network for trend analysis. The workstation network forms a CMMS that provides two types of functionality:

- Statistical analysis and data-mining techniques for detecting and predicting equipment failures, based on historical condition data and standards in the database.

- Real-time feedback to shipboard equipment operators, enabling more efficient use of maintainer time and also avoidance of potential catastrophic equipment failures.

ICAS does not provide an automatic link to the logistics support system, nor any long-distance communication of condition data to other ships or shore maintenance sites. ICAS also does not provide condition-monitoring coverage to ship defense systems or ship weapon systems as presently configured.

ICAS Diagnostic / Prognostic Functionality

| Functions | ICAS |
|---|---|
| Fault Detection | ● |
| Fault Isolation | IETM |
| Fault Prediction | ◑ |
| Fault Recovery | ○ |
| Fault Assessment | ○ |
| Fault Reporting | ● |
| Sensor-Coupled IETM | ○ |
| Logistics Trigger | ○ |

Ship Propulsion, Hull, Mechanical & Electrical Subsystems

# ICAS Diagnostic / Prognostic Functionality

ICAS supports basic CBM system diagnostic functionality, as ADIP does. Fault detection is an embedded condition-monitoring process, but isolating the fault is an O-level maintainer task using on-line documentation. Predictive capability is derived by collecting and storing condition data in a shipboard database for trend analysis and detection of potential equipment problems.

There is no capability for embedded autonomous fault assessment or recovery in the sense of prognostic operations. Neither is there a capability for built-in failure prediction, even though the system does do trend analysis, and a sailor may, at his discretion, call up a trend chart display and use it to forecast the requirement for a maintenance action. For this reason, we cite ICAS as having a partial capability for failure prediction.[8]

[8] Discussion with Ken Jacobs, NAVSEA04M, 20 July 2000.

### IMD-HUMS Overview

| | Program Description |
|---|---|
| | IMD-HUMS |
| Time horizon | 1998–2004 |
| Type of program | Commercial Operations & Support Saving Initiative (COSSI)/commercial partner is BF Goodrich |
| Scope of program | Helicopter fleets (principally Sikorsky): H-53E/SH-60/CH-60/S-92/S-76C/ S-76A (FAA) |
| Program goals | Improve helicopter operational readiness; improve flight safety; reduce maintenance-related costs; reduce dedicated maintenance flights |
| | |
| Technology | |
| On-Board H/W | Mechanical diagnostics, rotor track and balance, exceedance monitoring, engine monitoring, structural usage |
| On-Board S/W | Limited information |
| COTS Technology | Limited information |
| Open-Systems Architecture | Use of open commercial interface standards |
| Logistics Linkage | NALCOMIS |

# IMD-HUMS Overview

The IMD-HUMS is a Commercial Operations and Support Savings Initiative (COSSI) program. This is an Office of the Secretary of Defense (OSD)-sponsored program to accelerate fielding of dual-use technologies (i.e., commercial) that satisfy military needs and have high potential to reduce operations and support costs. IMD-HUMS stemmed from helicopter safety problems in the Presidential helicopter fleet; a 1993 White House requirement memo initiated the program.

The IMD-HUMS program integrates and tests a commercial/military "dual use" mechanical diagnostic system from BFGoodrich on the H-53 and H-60 Sikorsky helicopters. This program is coordinating with the Joint Advanced Health Usage & Monitoring System (JAHUMS), a separate CBM technology development project, in order to use the JAHUMS project for risk reduction in testing key technologies.

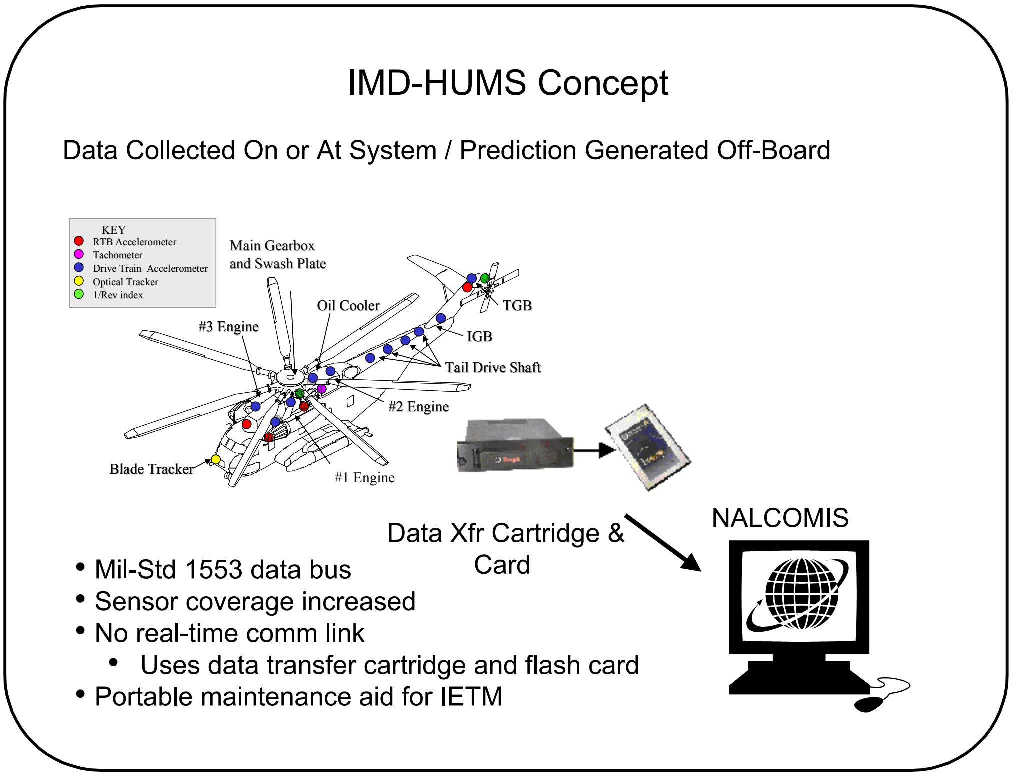
There are a number of other HUMS programs, domestic and international, that represent a source of lessons learned and potential collaboration. Internationally, both the United Kingdom Ministry of Defence and the Canadian Defence Forces have developed and fielded HUMS for helicopters. The U.S. Army PM-TMDE is sponsoring a HUMS program for the Army independent of both IMD-HUMS and JAHUMS, working with the South Carolina National Guard. These various efforts appear to be legitimate sources for effective collaboration.

### OBSERVED BENEFITS TO DATE

Based on a limited number of aircraft, the following data was reported by the program office: [9]

- A 13 percent reduction in scheduled maintenance due to accurate flight hour recording.
- A 10 percent reduction in total aviation depot-level reparables/consumable costs due to reduction in vibration-related maintenance actions.
- A 6 percent reduction in depot costs.
- A 2.8 percent total flight hour reduction due to a decrease in functional check flights on H-60; 3.7 percent on H-53.

[9] IMD-HUMS briefing to Congressional Budget Office, Col. Janowsky, 17 Dec 99.



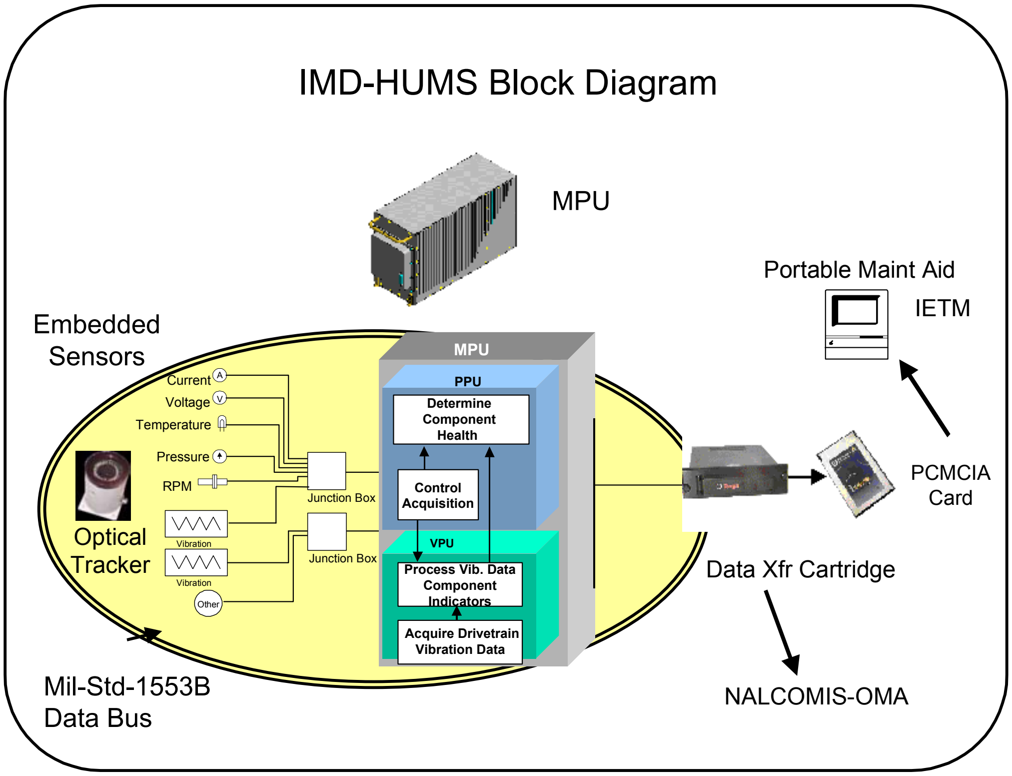

# IMD-HUMS Concept

IMD-HUMS provides for full-time in-flight monitoring and collection of engine and mechanical drive systems health information. This monitoring process includes flight regime information necessary to make prognostic forecasts of remaining equipment life, and structural and operational usage.

When the helicopter is on the ground, the data transfer cartridge containing in-flight condition data is retrieved and sent to the Naval Aviation Logistics Command Management Information System (NALCOMIS) Optimized Organizational Maintenance Activity (OMA**),** where it is analyzed for early identification and correction of degraded components in the engine, drive train, and rotor systems of the helicopter.[10]

IMD-HUMS provides for cockpit display, alerting aircrew of aircraft health data considered to have an impact on immediate flight safety. A portable computer functions as a portable maintenance aid running a traditional Class 3-4 IETM (i.e., not sensor-linked).

[10] IMD-HUMS briefing, Col. Janowsky, 22 February 2000.




# IMD-HUMS Block Diagram

Major on-board hardware components include: (1) the main processor unit (MPU), whose principal functions are shown in the chart, (2) an optical tracker unit, used for rotor track and balance evaluation, (3) data concentrators, and (4) an array of various sensors. Vibration and temperature sensor data are collected to aid flight regime analysis.

An IETM resides on a portable maintenance aid that reads a PCMCIA card loaded with selected in-flight condition data used to assist troubleshooting and repair.

IMD-HUMS On-Board / Off-Board Capabilities

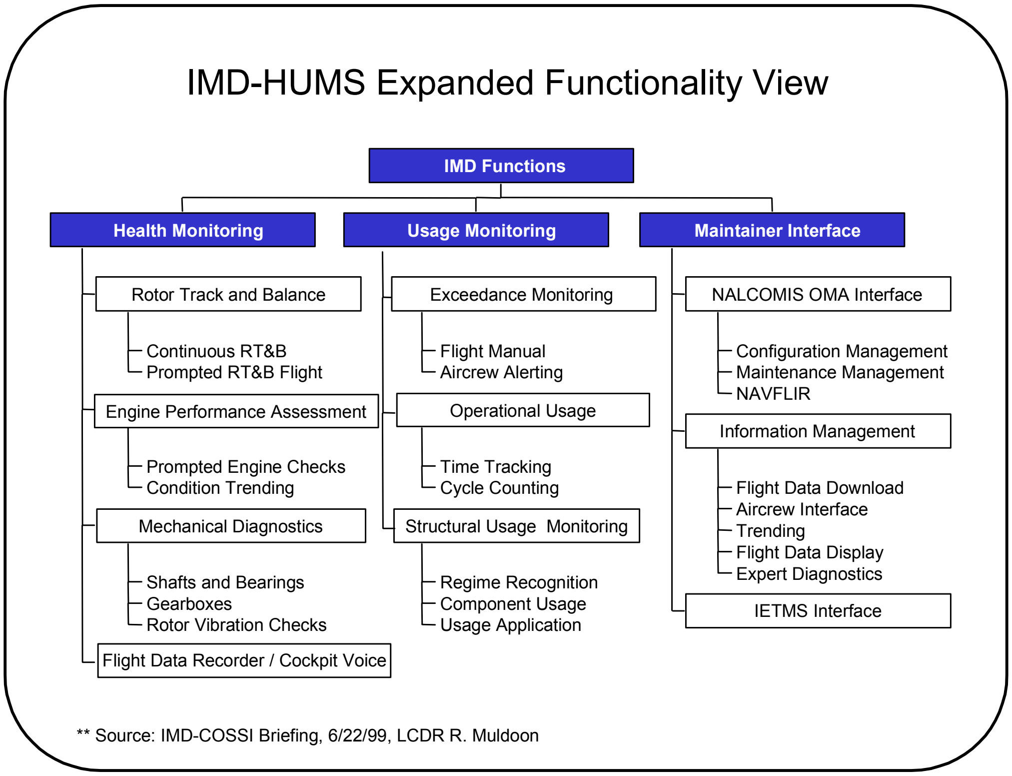
| On-Board | | | | | |
|---|---|---|---|---|---|
| Condition Monitoring | Data Collection | Communication | Reasoning | Event Detection and Isolation | Logistics Alert Trigger |
| ● | ● | ○ | ○ | ◑ | ○ |

| Off-Board | | | | | |
|---|---|---|---|---|---|
| Condition Monitoring | Data Collection | Communication | Reasoning | Event Detection and Isolation | Logistics Alert Trigger |
| ● | ● | ○ | ● | ● | ● |

# IMD-HUMS On-Board / Off-Board Capabilities

IMD HUMS goes beyond the capabilities of the basic CBM system developed as a reference. It has significant on-board sensor and computer technology and uses flight data recorder technology to record component health data and transfer that to NALCOMIS. IMD-HUMS also provides on-board aircrew alerting when equipment operating conditions impact flight safety.

IMD-HUMS does not provide in-flight downlinking of condition-monitoring data and does not include an interface to the logistics support system in real time.




# IMD-HUMS Expanded Functionality View

IMD-HUMS has a range of functionality worth additional exploration.[11] Twenty-four specific functions are identified above. Below we provide additional explanation in three key functional areas.

1. Rotor tracking and balancing (RT&B):

   - Automatically acquires rotor smoothing data and recommends adjustments; pilot may command acquisition.
   - Balance solution computed using vibration and track data (eight accelerometers and optical tracker).
   - Eliminates need for many dedicated RT&B flights.
   - Provides vibration manual equivalents for rotor system components.
   - Functionality provided in on-board system and ground based system.

2. Engine diagnostics:

   - Automates all power assurance checks (system prompts, data quality assurance, confirmation, and results).

[11] IMD-COSSI Briefing, 6/22/99, LCDR R. Muldoon.

- Limits exceedance recording and annunciation.
- Record of engine chip detector activation.
- Engine life usage and trending (operating hours, start and stops, LCF counts, thermal cycles, engine-out events, and/or stress rupture).
- Engine drive train degradation and failures.
- H-53E #2 engine thermal detector interface.

3. Gearbox and drive train diagnostics:

   - Provide diagnostics for all drive train components.

4. Automatic on-board processing with no user interface required under normal conditions.

.

IMD-HUMS Diagnostic / Prognostic Functionality

| Functions | IMD-HUMS |
|---|---|
| Fault Detection | ● |
| Fault Isolation | IETM |
| Fault Prediction | ● |
| Fault Recovery | ○ |
| Fault Assessment | ◑ |
| Fault Reporting | ● |
| Sensor-Coupled IETM | ○ |
| Logistics Trigger | ○ |

Helicopter propulsion, drive train, and structural subsystems

# IMD-HUMS Diagnostic/Prognostic Functionality

Fault detection: IMD-HUMS uses a sophisticated methodology for in-flight condition monitoring that approaches prognostic capability. A flightline maintainer performs fault isolation using a PMA-resident IETM augmented by helicopter health data collected on-board the aircraft and provided to the IETM via the PCMCIA card.

Fault prediction and reporting: IMD-HUMS provides significant capability for early detection of impending problems in the complex mechanical systems associated with the helicopter drive train by analyzing trends using collected in-flight equipment health data. Fault reporting is an integral part of equipment health and usage monitoring.

Fault assessment: IMD-HUMS accomplishes fault assessment and pilot alerting for flight safety concerns. It does not address fault recovery.

As mentioned earlier, IMD-HUMS does not downlink maintenance data, but provides data to NALCOMIS via a data transfer cartridge.

Program Description Summary

| | Program Description | | | |
|---|---|---|---|---|
| | JSF=PHM | ADIP | ICAS | IMD-HUMS |
| Time horizon | 2000 – 2037 | 1998 – 2005 | 1997 – 2003 | 1998 – 2004 |
| Type of program | Pre-procurement/Entering Engineering and Manufacturing Development (EMD) in 2001 | Legacy systems | New ships and legacy ships | Commercial Operations and Support Saving initiative (COSSI) / Commercial partner is BF Goodrich |
| Scope of program | USAF & RAF air-air, air-gnd; USMC STOVL; Navy carrier aircraft | All combat vehicles, missiles and aircraft; all support vehicles and aircraft; all mobile electric power | All Navy surface fleet ships | Helicopter fleets: H-53Es / SH-60s / CH-60s / S-92 / S-76C / S-76A (FAA) |
| Program goals | To enable Autonomic Logistics, and through that, to maximize sortie generation rates and mission reliability, to reduce the logistics footprint, and to eliminate false alarms | Reduce NEOF by 50 percent<br>Reduce O&S costs by 20 percent<br>Reduce life cycle costs for all systems<br>Redesign the diagnostics business process to establish an electronic link from the weapon system to the GCSS-A | To automate the preparation of the ship logbook | Improve helicopter operational readiness<br>Improve flight safety<br>Reduce maintenance-related costs<br>Reduce dedicated maintenance flights |
| | | | | |
| Technology | | | | |
| On-board H/W | Sensor, actuator and microprocessor intensive environment, tailored for PHM | Diesel-powered vehicles using SAE std data bus and sensors; engine/trans/ABS control units (ECU) as designed by commercial vehicle OEMs | No embedded sensors or computers in older ships. Newer gas turbine-powered cruisers and destroyers have both embedded sensors and data bus. Ship has network of CMMS workstations | Mechanical diagnostics, rotor track and balance, exceedance monitoring, engine monitoring, structural usage |
| On-board S/W | Hierarchy of prognostic software reasoning systems | Diagnostic messages generated by the ECUs | No embedded software, except for systems mentioned above. IDAX CBM software runs on the CMMS network | Limited information |
| COTS technology | Microprocessors, interfaces to information systems | Data bus, sensors, ECU, message protocol | ICAS system adapted from commercial IDAX application | Limited information |
| Open-systems architecture | Limited | Yes | Yes | Use of open commercial interface standards |
| Logistics linkage | Triggered by on-board prognostic software to multiple logistics information systems | Triggered by off-board statistical analysis within GCSS-Army | Not linked | NALCOMIS |

# Program Description Summary

## PROGRAM ELEMENTS

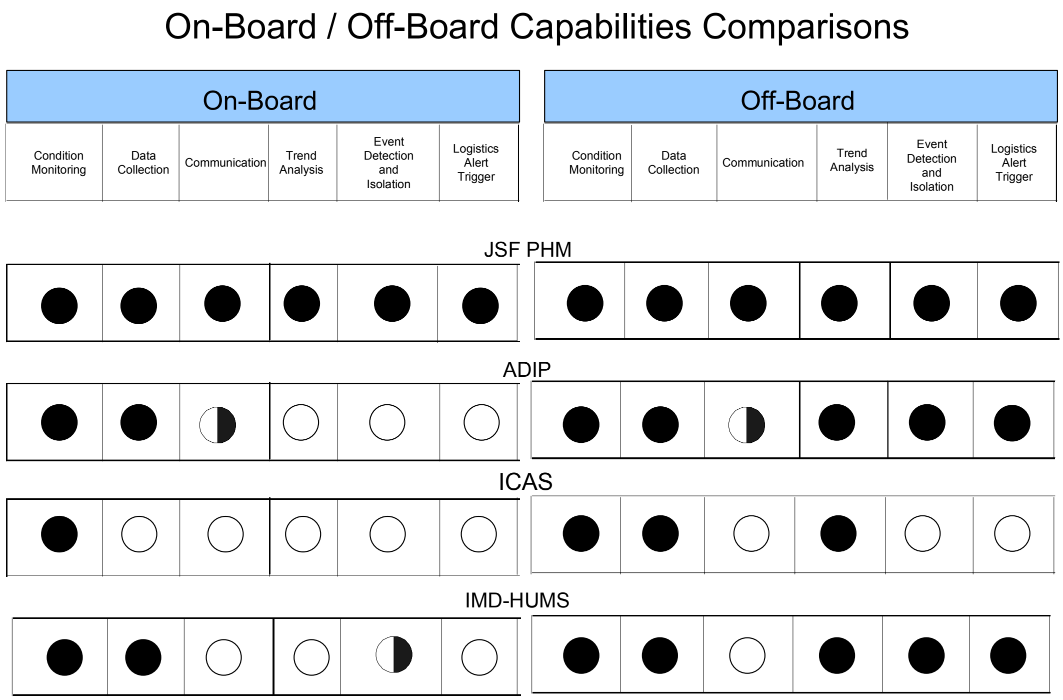
JSF PHM is the most comprehensive technology development program reviewed for this report. It is the DoD leader in technical capability and in the articulation of program goals measured by appropriate metrics. And it has the longest time horizon (>40 years). Additionally, JSF PHM is built upon an open-systems architecture with the integration of COTS technology where feasible. It has pioneered the concept of autonomic logistics.

ADIP addresses the most diverse fleets of weapon systems and the greatest numbers and kinds of equipment. ADIP has pioneered the technology-enhanced, sensor-coupled IETM. It has a vision of achieving embedded PHM capability similar to the JSF program, but present capability uses a PMA-centric approach to capture and transmit equipment health data to a processing center that can mine the data for predictive information. ADIP has worked extensively with GCSS-Army to develop and augment GCSS-Army with a predictive maintenance module capacity and has specified the software interfaces and data elements needed to accomplish this. The goals of ADIP are the most specific shown, but still to be developed are program metrics to monitor progress in attaining those goals.

ICAS addresses the most substantial technical challenges reviewed in this report as measured by the range and kinds of older non-digital ship propulsion and

HM&E systems it attempts to address. It limits CBM goals to cost reduction in the form of reducing man-hours spent recording data in the ship logbook, and does not address logistics support linkage or integration. Technically, ICAS is an adaptation of the trademarked COTS CBM system from IDAX, Incorporated, and is self-contained on each ship that implements ICAS.

IMD-HUMS is more a platform-specific project than a Service CBM program, but it does address multiple helicopter fleets. It has designed a sophisticated methodology for in-flight condition-monitoring that approaches prognostic capability. It does not attempt real-time condition-reporting or downlinking data while in-flight, but it does provide significant capability for early detection of impending problems in many complex mechanical systems associated with the helicopter drive train.




# On-Board / Off-Board Capabilities Comparison

This chart shows a side-by-side comparison of the capabilities of each CBM program. The JSF PHM system stands out as the only full-suite prognostic program capable of on-board prognostic reasoning based on model-based software. JSF PHM is also the only program that includes automatic triggering of the logistics support system on a real-time basis while the weapon system is in operation (i.e., in flight).

ADIP reflects basic CBM capability, but has near-real-time communication of on-board condition data when augmented by the TACOM telemaintenance system. ADIP's long-range plan is to achieve embedded predictive capability, though it may not achieve the prognostic capability of JSF PHM.

ICAS also reflects basic CBM capability, but in a different manner than ADIP. ICAS is a self-contained shipboard system in which the maintenance workstation network used to analyze condition data is also shipboard.

IMD-HUMS goes beyond basic CBM capability by embedding a significant hardware and software health monitoring system on the helicopter. The embedded health monitoring system links to the logistics support system by a data transfer cartridge that is retrieved from the helicopter after landing and sent to the appropriate maintenance activity.

## Diagnostic Functionality Summary

| Functions | JSF | ADIP | | ICAS | IMD-HUMS |
|---|---|---|---|---|---|
| | | Ground System | Army Helicopter | | |
| Fault Detection | ● | ● | ● | ● | ● |
| Fault Isolation | ● | IETM | IETM | IETM | IETM |
| Fault Prediction | ● | ● | ● | ◐ | ● |
| Fault Recovery | ● | ○ | ○ | ○ | ○ |
| Fault Assesment | ● | ○ | ○ | ○ | ● |
| Fault Reporting | ● | ● | ● | ● | ● |
| Sensor-Coupled IETM | ● | ● | ○ | ○ | ○ |
| Logistics Trigger | ● | ● | ○ | ○ | ○ |

# Diagnostic Functionality Summary

This chart depicts our comparative characterization of the capabilities of the four CBM systems. Only JSF PHM covers the spectrum of functionality shown in the table. All systems accomplish the functions of fault detection, fault prediction and fault reporting. The approach used to achieve the predictive capability and fault isolation is a key differentiating character.

The IETM capability noted for ADIP refers to the technology-enhanced, sensor-coupled nature of that IETM as opposed to a simpler form of computer readable IETM. All CBM systems use an IETM that is hosted on a portable maintenance aid. The difference is in how the IETM works with the embedded CBM technology to assist the maintainer in isolating a fault. JSF fault isolation is designed to isolate 80 - 90 percent of all faults on-board, leaving the IETM with a 10 percent diagnostic requirement and a 90 percent requirement to execute repair procedures. Therefore, JSF can use a "thin-client" architecture for its PMA, getting the necessary repair instructions from a networked maintenance server. IMD HUMS boosts the IETM fault isolation process by providing a PCMCIA card with in-flight condition data to aid the troubleshooting process.

Fault prediction for all systems but JSF PHM relies on trend analysis performed by an off-board network of maintenance workstations with a large database of equipment health data. JSF uses on-board model-based reasoning software to isolate and predict faults through a combination of sensor inputs and inferences based on operating conditions and off-board trend analysis.

Best Practices

| | JSF | ADIP | ICAS | IMD-HUMS |
|---|---|---|---|---|
| Goal-Setting & Payback Evaluation | ● | | | |
| Prognostic Functionality | ● | | | ● |
| Technology Spin-Off | ● | | | |
| COTS Technology | ● | ● | ● | |
| Open-Systems Architecture | ● | ● | ● | |
| Service-Level Information System Integration | ● | ● | | |
| Autonomic Logistics Triggering | ● | | | |

● Best Practice

# Best Practices

For elements such as those identified in this chart, sharing best practices with other programs could contribute to streamlined planning, increased cost-effectiveness, and mission-improved CBM systems. These “best practice” elements have been discussed earlier in this briefing; we plan to provide more detailed assessments in future reports and briefings. Programs may benefit from an understanding of areas such as planning, technology, and implementation issues within other programs.

The JSF PHM program is the most strategically significant CBM program in DoD. But it is not alone in best practices, as indicated in the chart. There are often many paths to the same goal.  Each of the Service programs has something to offer military planners of CBM systems. Additionally, from a weapon system PM perspective, any single approach may not offer the capability sought, but the programs in aggregate certainly will.

Overarching Issues

- Maximizing CBM Effectiveness
- Retrofitting Legacy Systems: The Impact of Open Systems Architecture
- DoD Advocacy For CBM & Best Practices

# Overarching Issues

The techniques of reliability-centered maintenance–or some derivative of the process–provide the strategic maintenance systems engineering necessary to maximize CBM effectiveness. CBM techniques need to be focused on the right tasks; selecting the right tasks should precede the selection of CBM technologies. Doing this will avoid unnecessary expense and resource use.

Most of the weapon systems we have in the field will be with us for the next decade. Some of this equipment was built well before CBM hardware and software was available on a built-in basis. Establishing a program of CBM for these legacy systems should be focused on specific opportunities. As we cited for the surface Navy, there is such a wide range of older technology in use that retrofitting CBM technology on a broad basis or for certain functions/subsystems may not be cost-effective.

The issues involved in substituting commercial technology for militarized technology require a case-by-case examination, particularly in the hardware ruggedization area. The opportunities to achieve this kind of process substitution are, however, more viable than once considered possible. We showed in our discussion of how CBM technology works where OSA/COTS emphasis plays a key role.

Recent DoD studies including the OSA-IDD study[12] in 1998 and the background investigations for this report, indicate the essential requirement to base CBM hardware and software architecture on an OSA approach. The OSA approach is used in all the major CBM programs evaluated in this report and is also cited in the OSA-IDD report in cases for the Aegis weapon system and V-22 Osprey tilt-rotor aircraft. Virtually every major Service CBM program has demonstrated that an OSA approach capable of using commercial technology is not just beneficial; it is a key element to successful retrofit of the technology on a cost-effective basis.

To move forward with CBM as a maintenance strategy, DoD needs a CBM advocate. The advocate should keep the Services focused on overall maintenance solutions rather than allowing a narrow focus on maintenance technology. There are many efforts underway for various aspects of technical development and technology maturation. What may be most beneficial at a macro-level is an advocate who can move doctrine, policy, and programs forward.

Each of the major Service CBM programs offers some lessons learned and process improvements that can benefit other weapon systems, regardless of Service or technology orientation. The JSF-PHM program is the visionary leader on all fronts, from concept to implementation, and across the various technologies of condition assessment and management to logistics system functionality and autonomic response.

JSF-PHM is not, however, the only visionary program within the Services. The Navy has agencies in NAVAIR and NAVSEA that have been addressing condition-monitoring and CBM for multiple systems as opposed to a single system. The Army's ADIP is unique in that it is implementing and integrating information from COTS-based technology at the GCSS information system level.

Because of the wide variation among CBM program technical approaches to achieve similar goals, some programs may be more successful than others in achieving their goals. Given that cost-reduction is a key theme in all CBM programs, it would be helpful and prudent from a DoD viewpoint if CBM programs were, at a minimum, similarly successful with respect to return on investment.

It will take routine collaboration to share the good ideas emanating from each of these programs and to cross-pollinate the technologies and program planning efforts. Such approaches, when successful, can reduce the risk that one or more programs will be sub-optimal in achieving their goals. Collaboration in CBM development should extend to industry and Service programs. For example, the industry consortium MIMOSA, mentioned earlier in this report, could be helpful in getting a profit perspective on CBM program investments in gaining insights into other technologies across a broad spectrum of industrial applications.

[12] Final Report and Roadmap, January, 1999, *Open Systems Approach - Integrated Diagnostic Demonstration Study*. Automatic Test Systems Executive Agent Office (ATS-EAO), NAVAIR PMA-260, Naval Air Station Patuxent River, MD.

Actionable Issues

**ADUSD(L), MPPR can encourage, incentivize and focus inter-Service collaboration for condition-based maintenance**:

- Make Condition-Based Maintenance an agenda item for meetings of the Maintenance Technology Senior Steering Group (MTSSG).
- Establish & Conduct a track for CBM, in conjunction with the DoD Maintenance Symposium.
- Increase visibility with the National Defense Industrial Association (NDIA) Systems Engineering committee and the Supportability and Integrated Diagnostics sub-committees.
- Establish a continuing on-line forum for inter-service CBM collaboration on the MPPR web site, linking commercial, DoD and academic areas of interest in CBM.
- Act as the DOD Advocate for CBM.
  - Monitor funding issues;
  - Influence Service goals-setting, program metrics and progress monitoring;
  - Encourage RCM practice.

# Actionable Issues

We suggest that the ADUSD(L)MPP&R take several steps to increase awareness of CBM as a maintenance approach and to ensure that the Department's efforts to explore CBM concepts are well coordinated and effective. Our suggestions for initial actions are:

- ◆ Involvement of the MTSSG: Initial and recurring review of CBM by the Maintenance Technology Senior Steering Group (MTSSG) can help focus high-level visibility on CBM progress and issues.
- ◆ Collaboration at the 2000 DoD Maintenance Symposium: Operating a CBM track at the upcoming DOD Maintenance Symposium will provide a working-level forum for the exchange of management and technology ideas across Service, functional, and program boundaries.
- ◆ Continued use of NDIA panel structure: The NDIA sponsors a number of committees and subcommittees concerned with weapons system supportability, logistics and maintenance. The senior committee that crosses interdisciplinary boundaries is the systems engineering committee, with its subcommittees for supportability and integrated diagnostics (both of which are affected by and project influence on CBM technology and management).

- Increased visibility through web site: Adding CBM to the existing ADUSD(L)MPP&R web site will increase awareness of CBM and its application in DoD. The site could further enhance ongoing collaboration among the Services and with industry.

We suggested that DoD needs an advocate who can focus the currently disparate CBM centers of excellence and cross-feed best practices. Taking the actions cited above, and others that emerge from these initial efforts, will establish DoD advocacy. ADUSD(L)MPP&R is the right office to act as the advocate for CBM. In addition to those actions outlined above, we suggest that the ADUSD(L)MPP&R:

- Monitor programmatic issues
- Influence Service goal-setting, program metrics, and progress monitoring
- Encourage reliability-centered maintenance practices and implementation that contribute to CBM effectiveness